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H4L LCAX LX4 L1CC L1CX
E1F FHK
H1Q QJE
H1T T1F T12 T15 T7A10B T7C6 T9

(56) Documents Cited
GB 2292869 A **GB 2153410 A** **EP 0295178 A2**
US 4800385 A **US 4739325 A**

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UK CL (Edition R) **E1F FHK , H4L LCAX LCC LCX**
INT CL^7 **E21B 47/12 , G01V 3/24 3/26 3/28 3/30 3/34**
Online: WPI, EPODOC

(54) Abstract Title
Borehole communication system

(57) Downhole apparatus for measurement-while-drilling (MWD) comprises a transmitter 52 with a stack of parallel-connected transmit coils, and a receiver 51 with a stack of series-connected receive coils. The receive coils are smaller in size than the transmit coils but are otherwise similar, each coil having a winding (37, Fig. 3a) on a toroidal core (36) and screening provided by a copper sleeve and end plates (38). The coils may be insulatedly mounted in a recess in a section of the drill collar (Fig.4a), or may be mounted along the axis of the drill collar (Fig.7e), or disposed in a pressure housing surrounding the drill collar (Fig. 8b). In use, the transmit coils can operate in an inductive mode to induce currents into the drill collar and drill string, and the coils also induce EM waves into the surrounding strata; alternatively, the transmit coils can be switched to a mode in which they are connected to the drill string so that they become a load coil for the drill string which acts as a dipole antenna (Figs.9a-c).

The surface system has a drill string transceiver (40, Figs. 10a,b) and a riser/casing transceiver (41) which have similar toroid assemblies to the downhole apparatus. An EM wave receiver (104) with horizontal dipole antenna system is also provided at the surface. Data received by each of the three units (40, 41, 104) may be compared for verification.

The system may have means for adjusting operating parameters in response to detecting environment-dependent conditions. An optimisation procedure (Figs. 13,14) may be used to adjust transmit power, carrier frequency, drive impedance, modulation type, data coding, and inductive versus dipole drive mode.

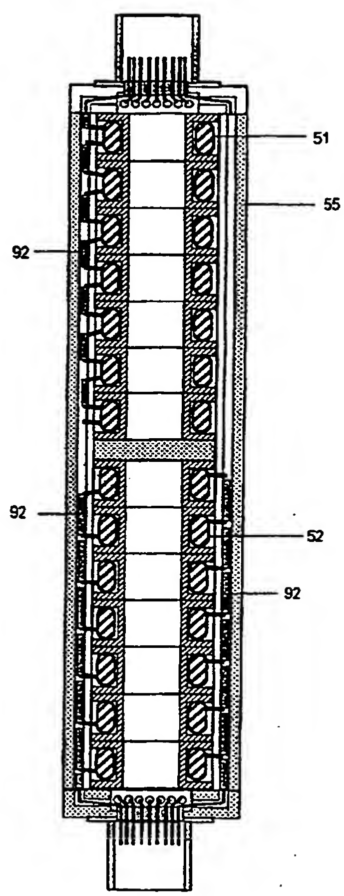

Fig. 7c

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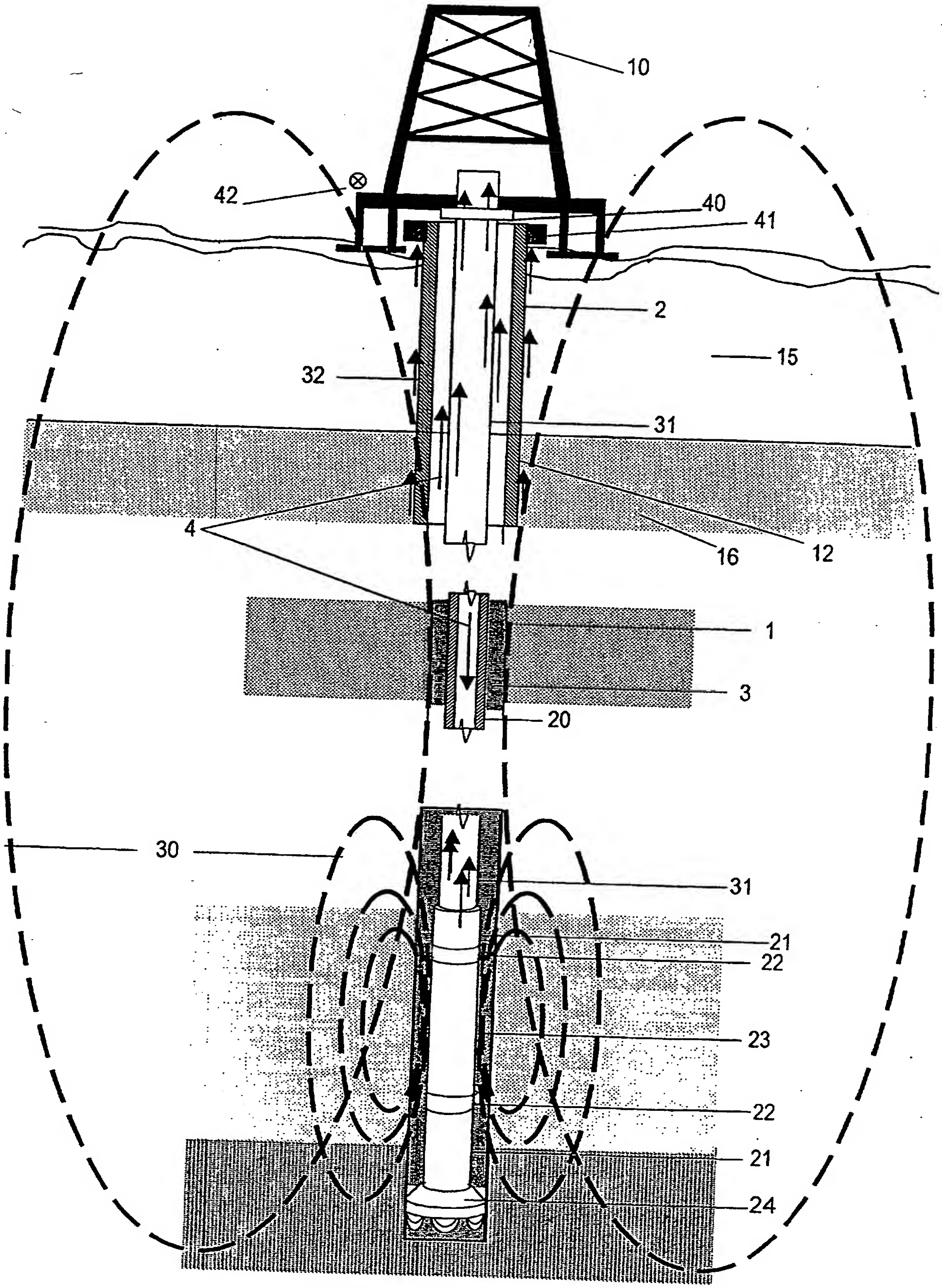
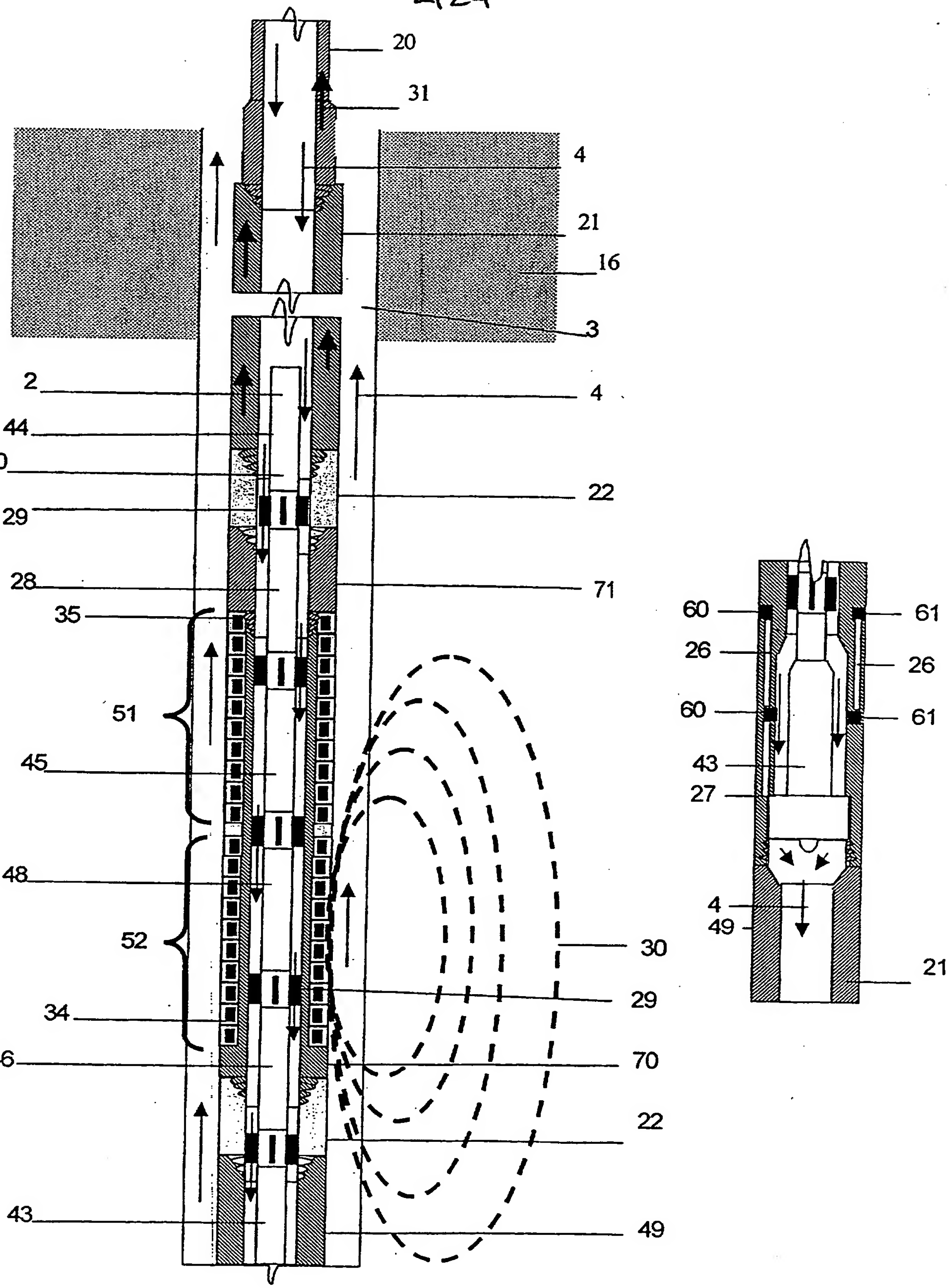


Fig. 1a


20
31
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16
3
2
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90
22
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48
52
34
46
43
30
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60
61
26
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60
61
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27
4
49
21

Fig. 1b

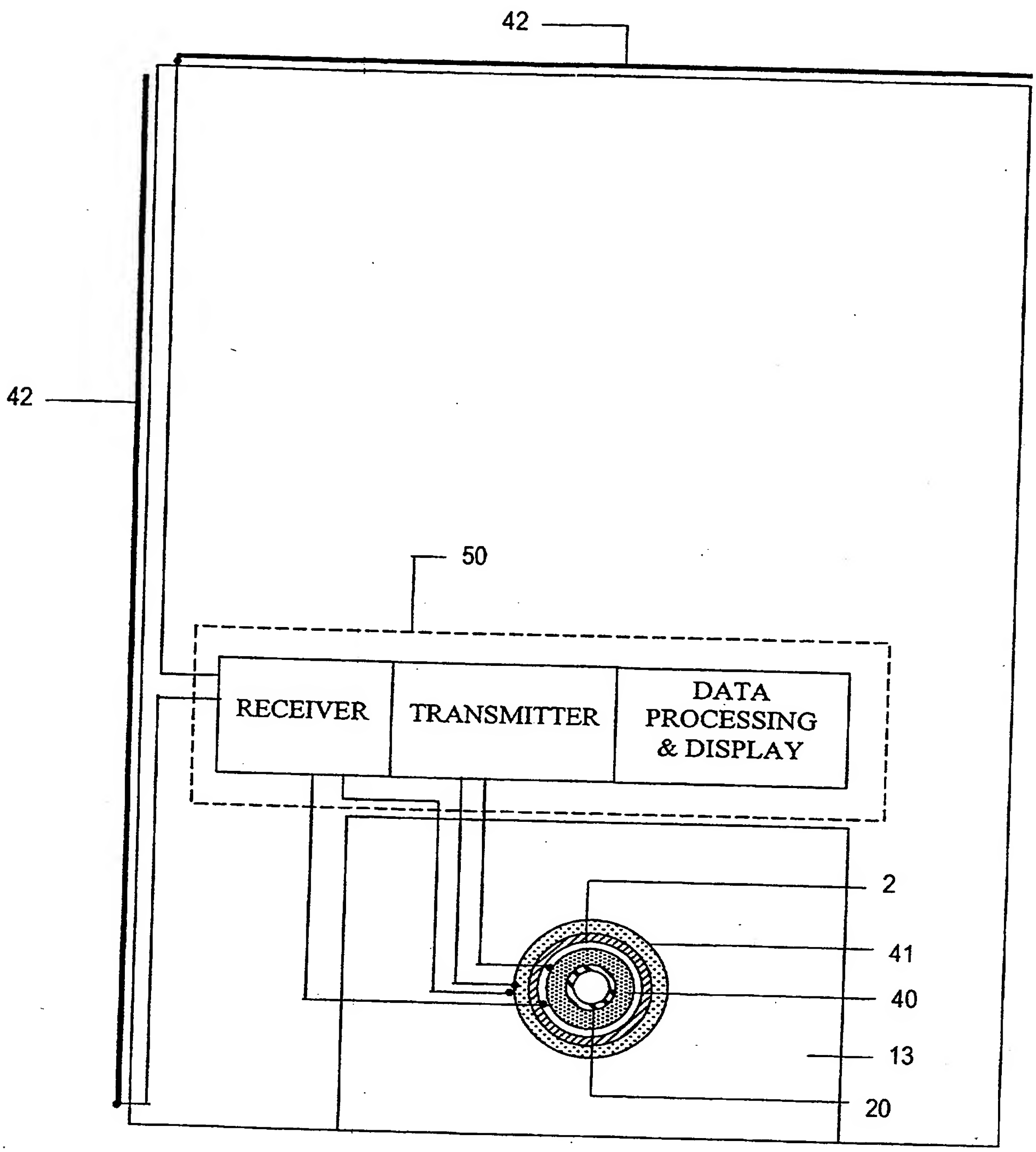

42
42
50
RECEIVER
TRANSMITTER
DATA PROCESSING & DISPLAY
2
41
40
13
20

Fig. 2

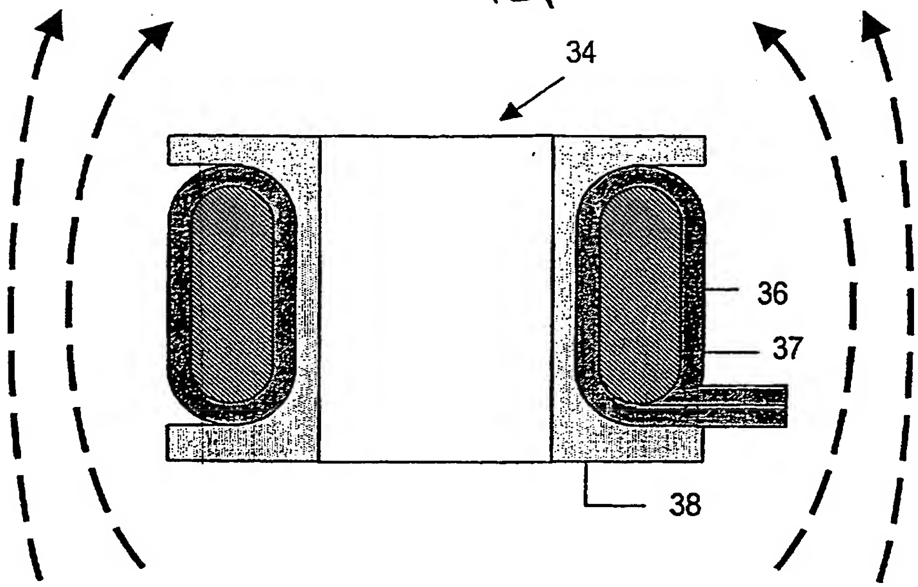


Fig. 3a

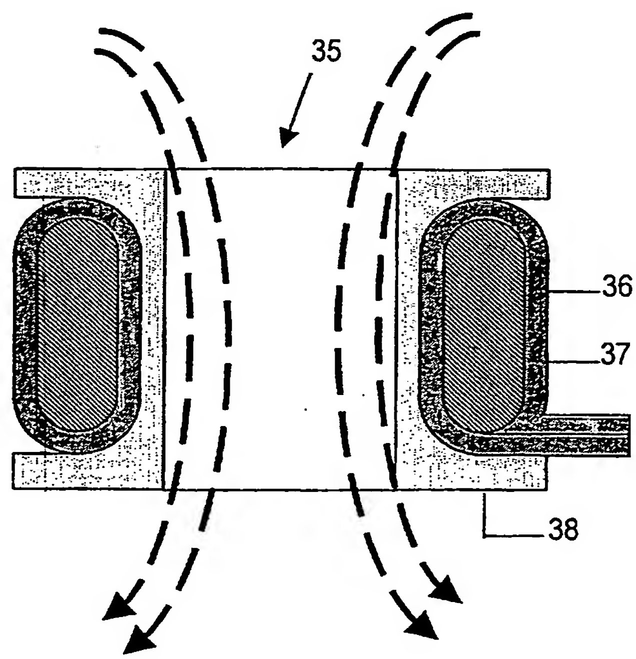


Fig. 3b

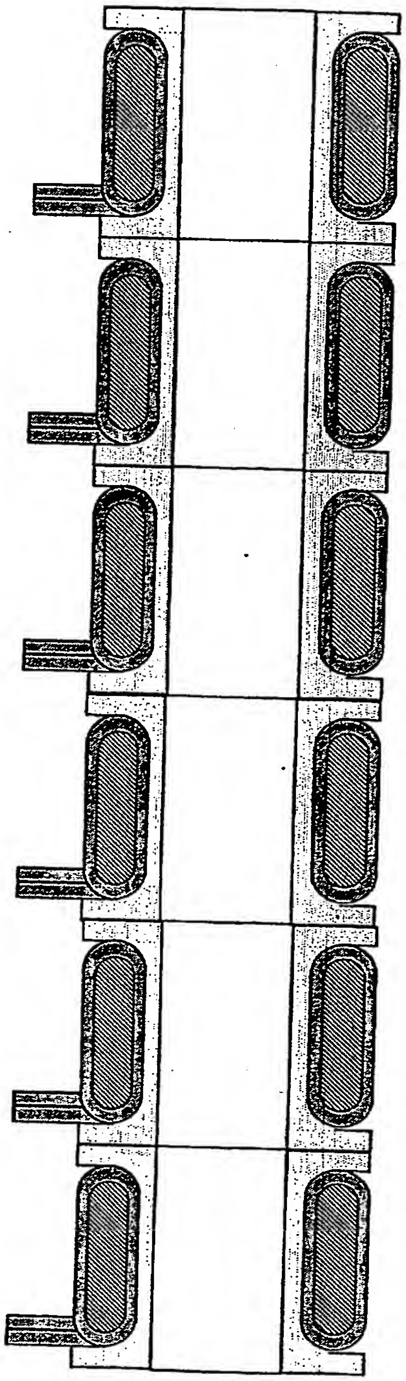


Fig. 3c

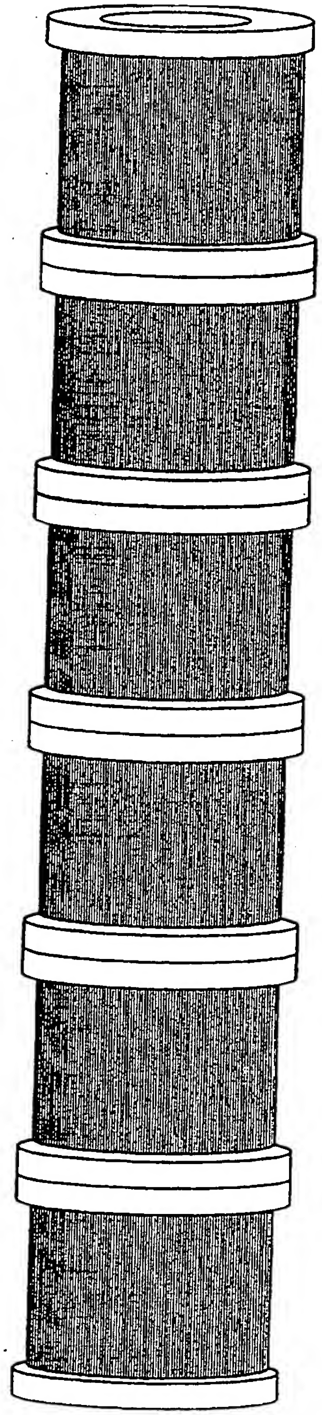


Fig. 3d

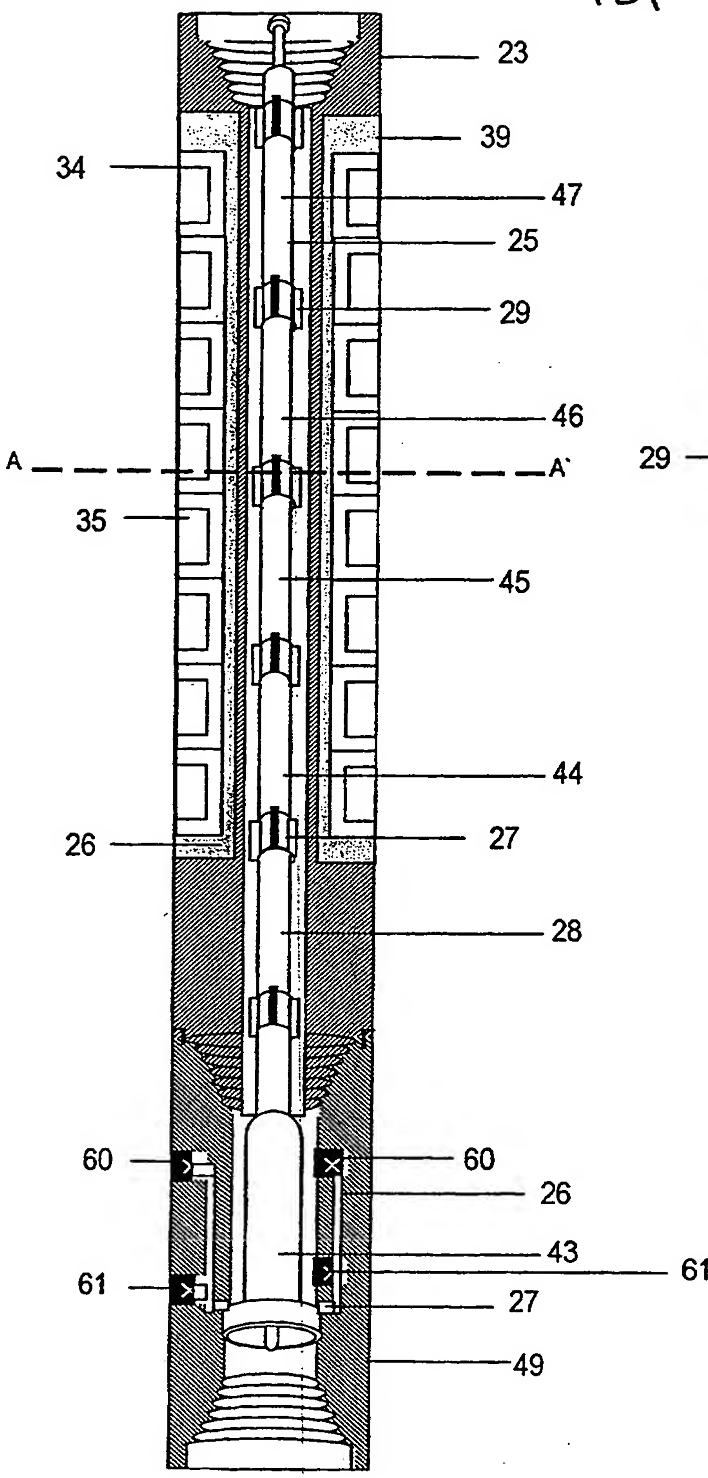


Fig. 4a

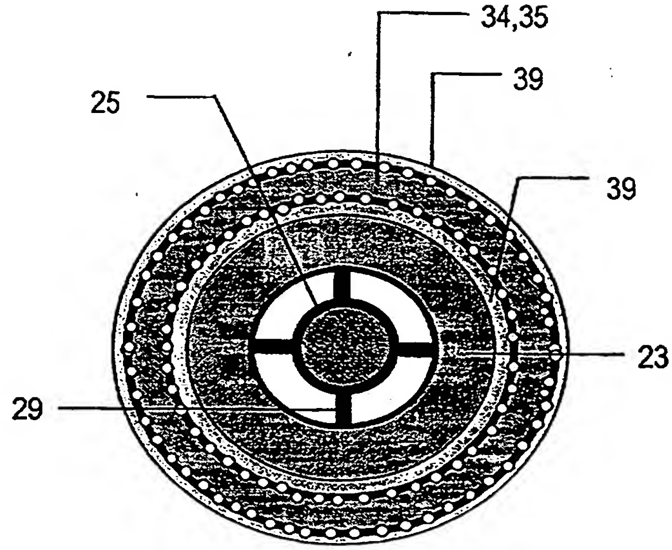


Fig. 4b

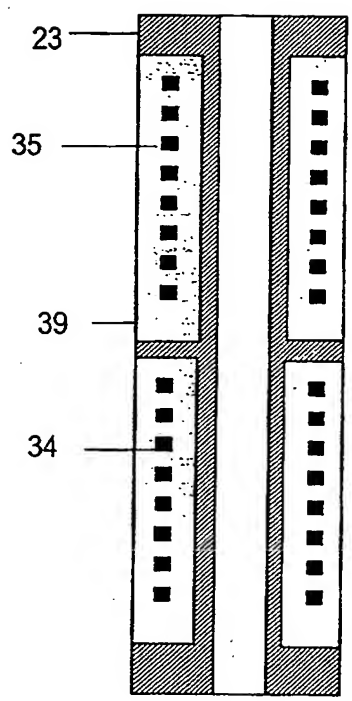


Fig. 4c

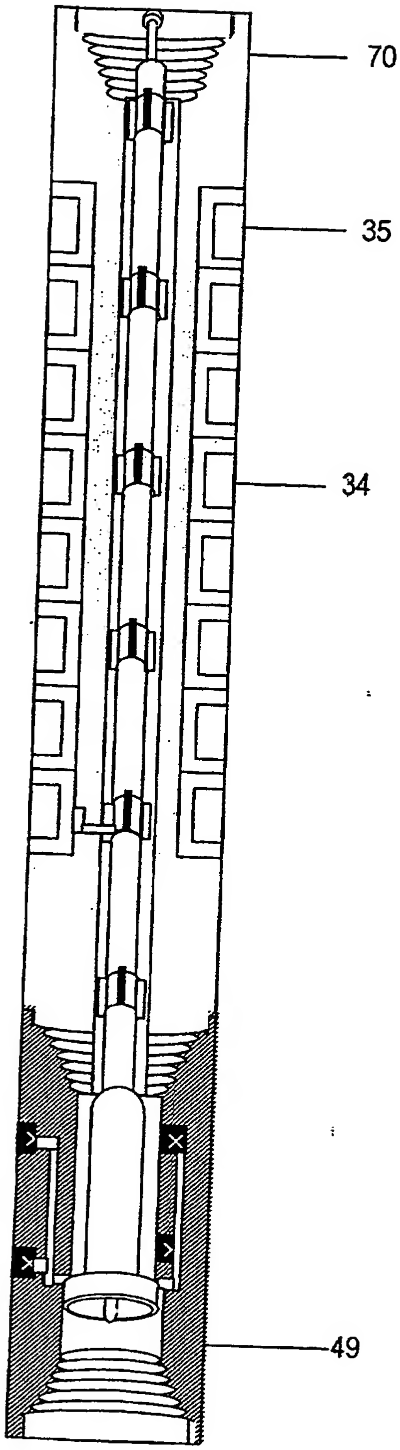


Fig. 5a

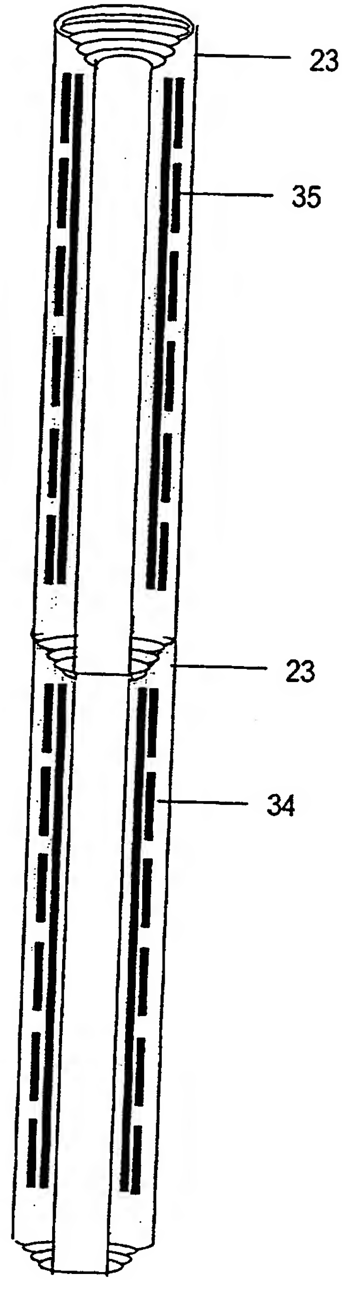


Fig. 5b

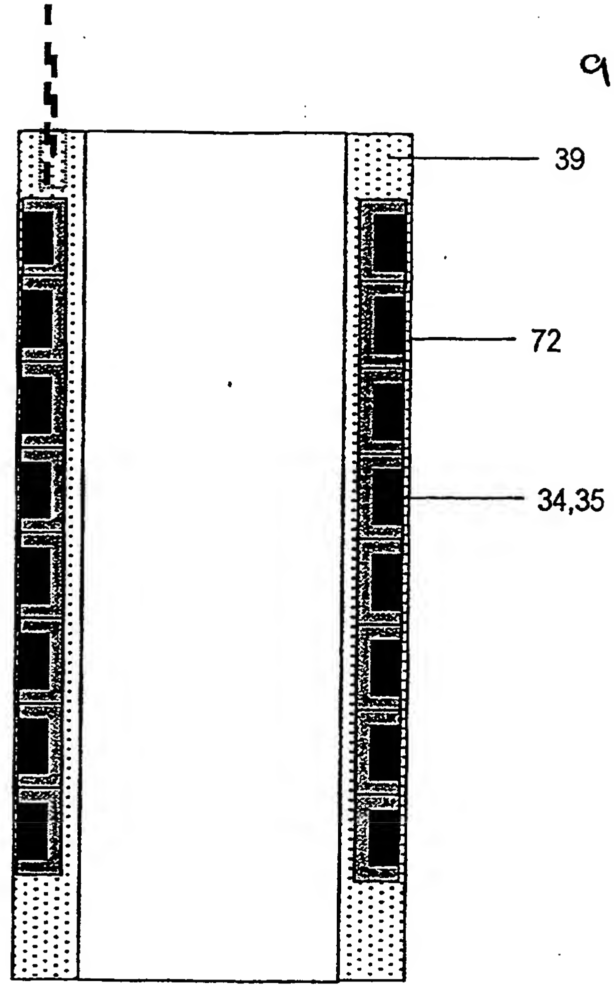


Fig. 6c

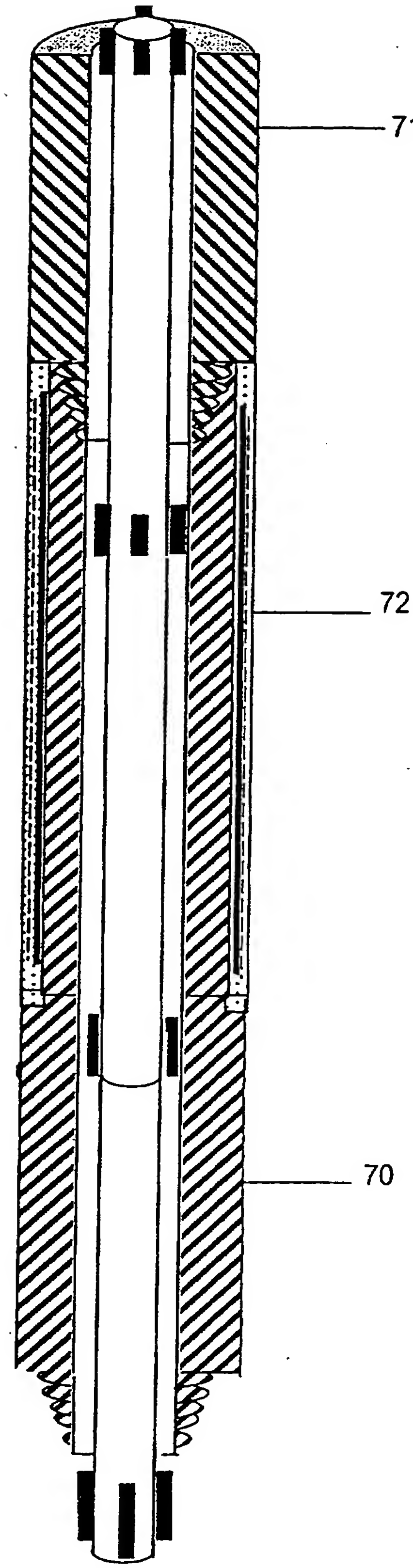


Fig. 6d

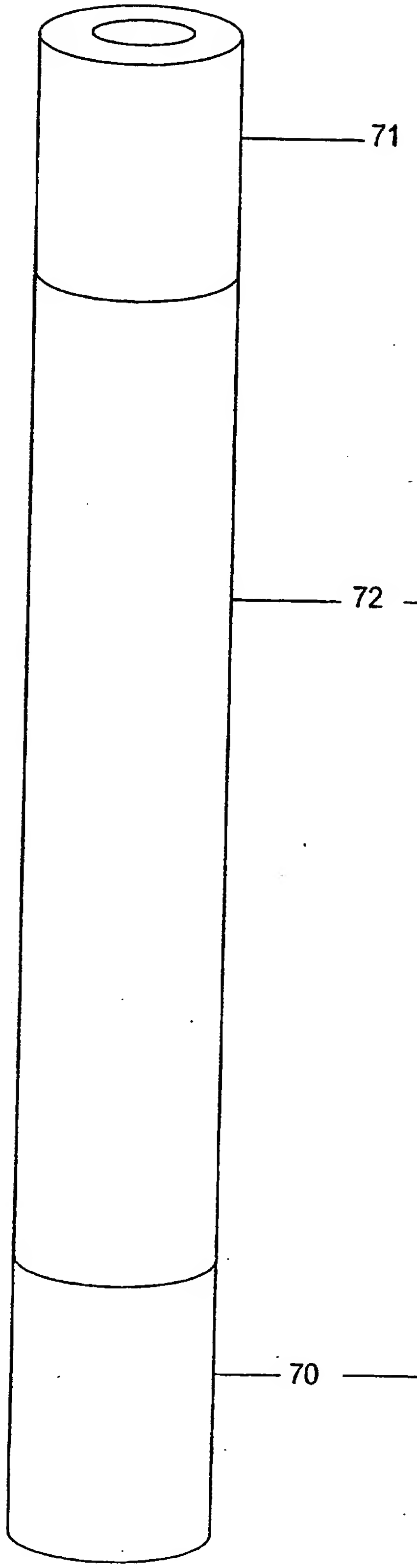


Fig. 6a

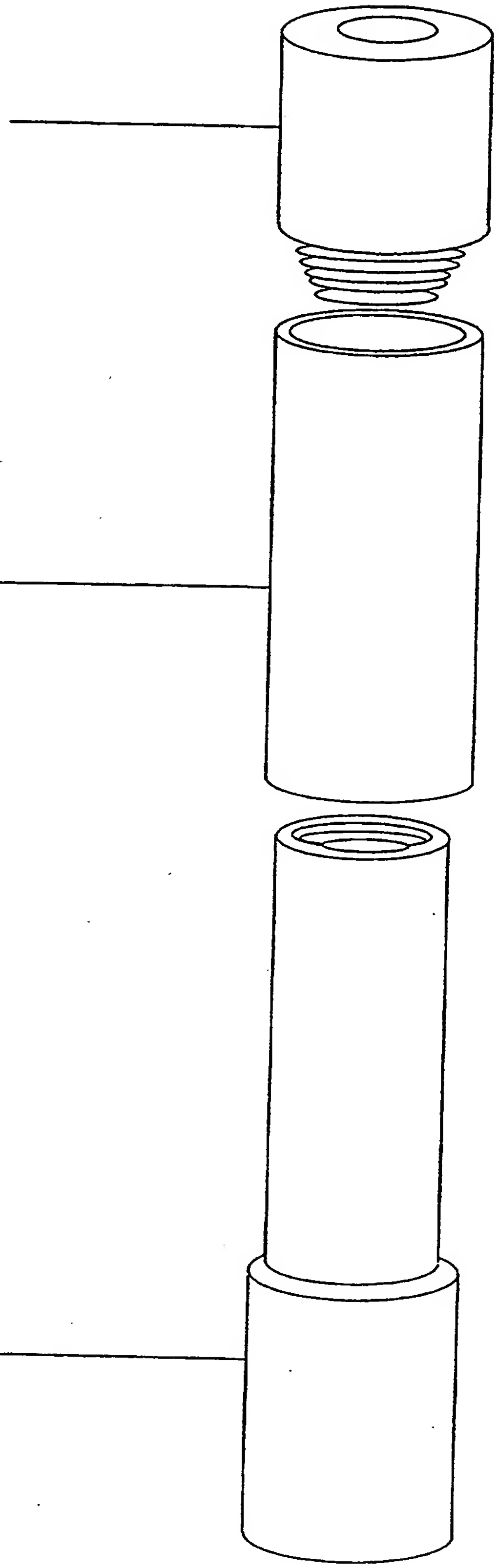


Fig. 6b

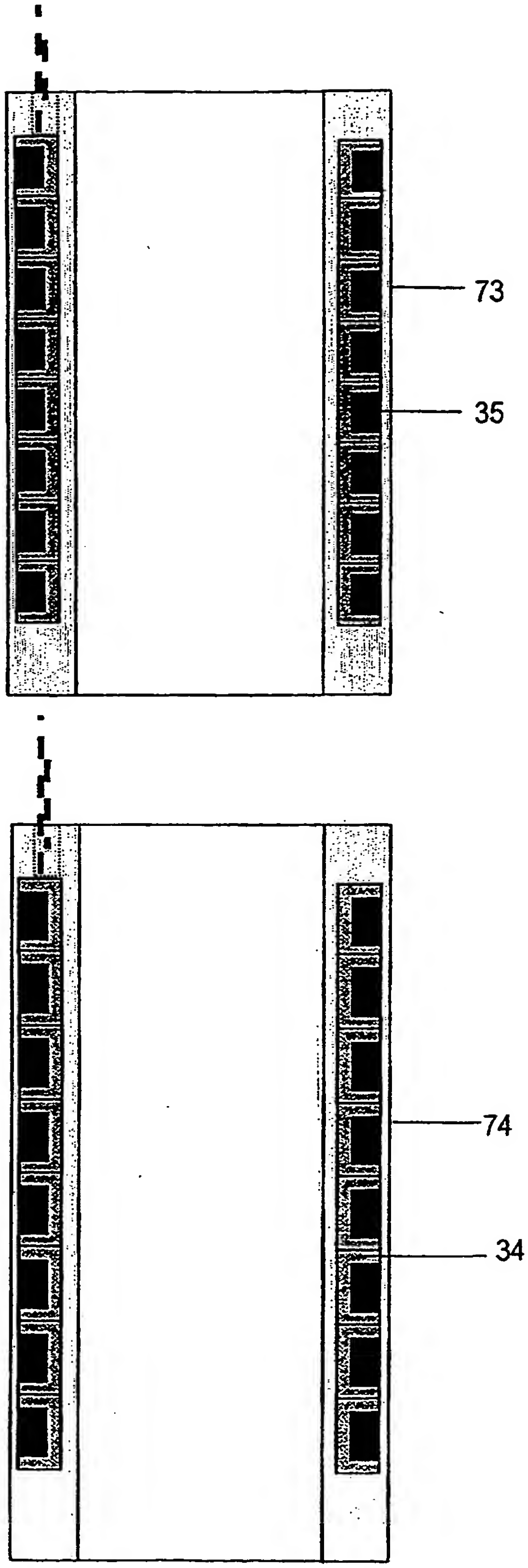


Fig. 6e

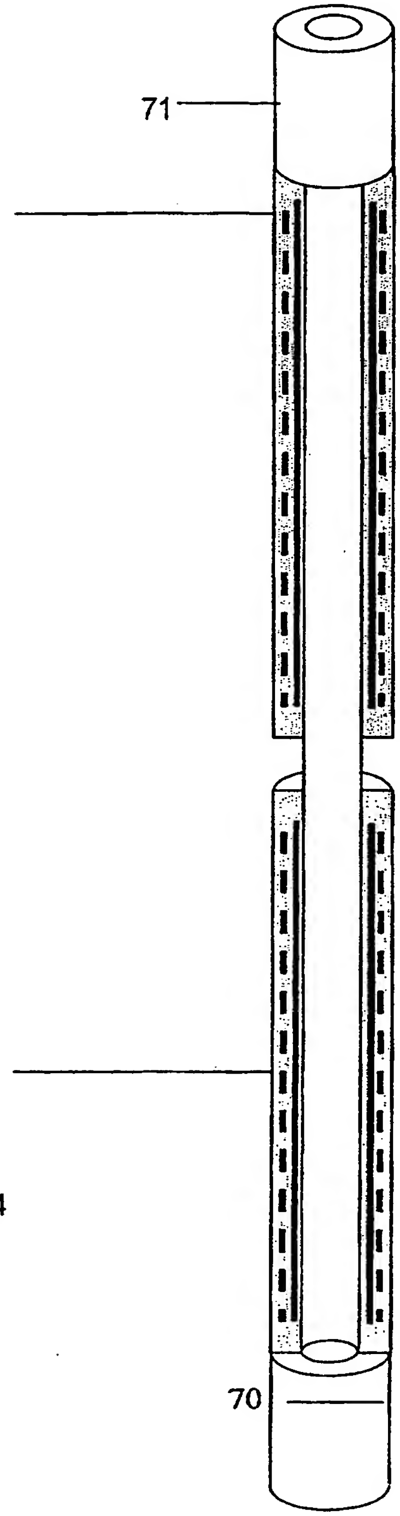


Fig. 6f

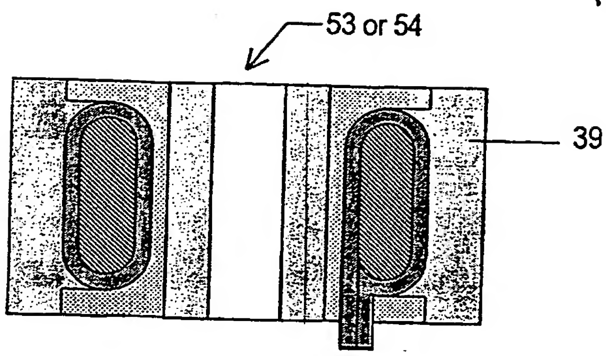


Fig. 6h

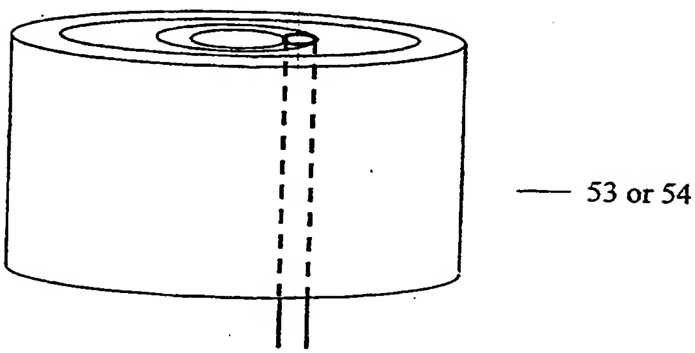


Fig. 6g

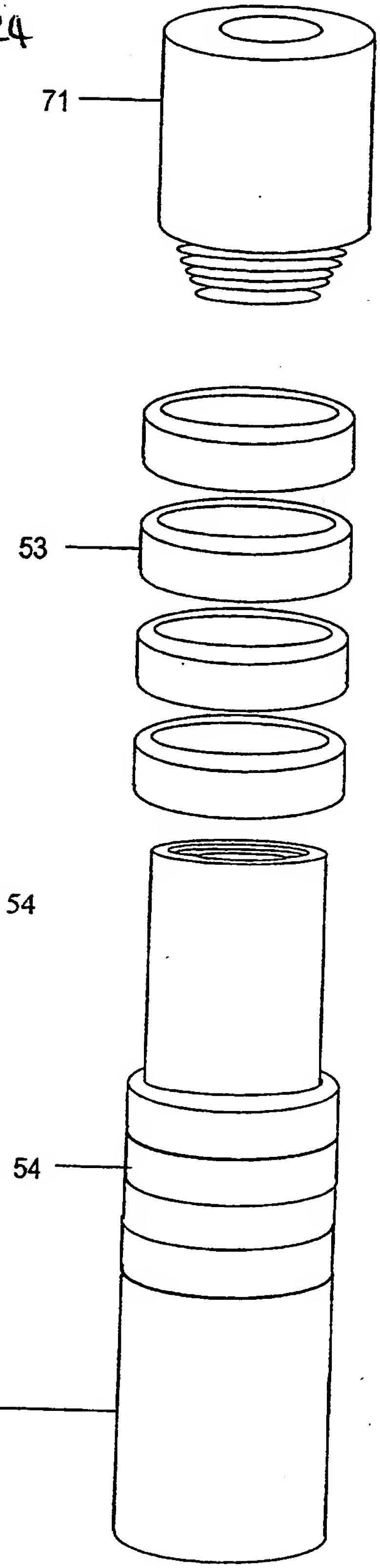


Fig. 6i

12/24

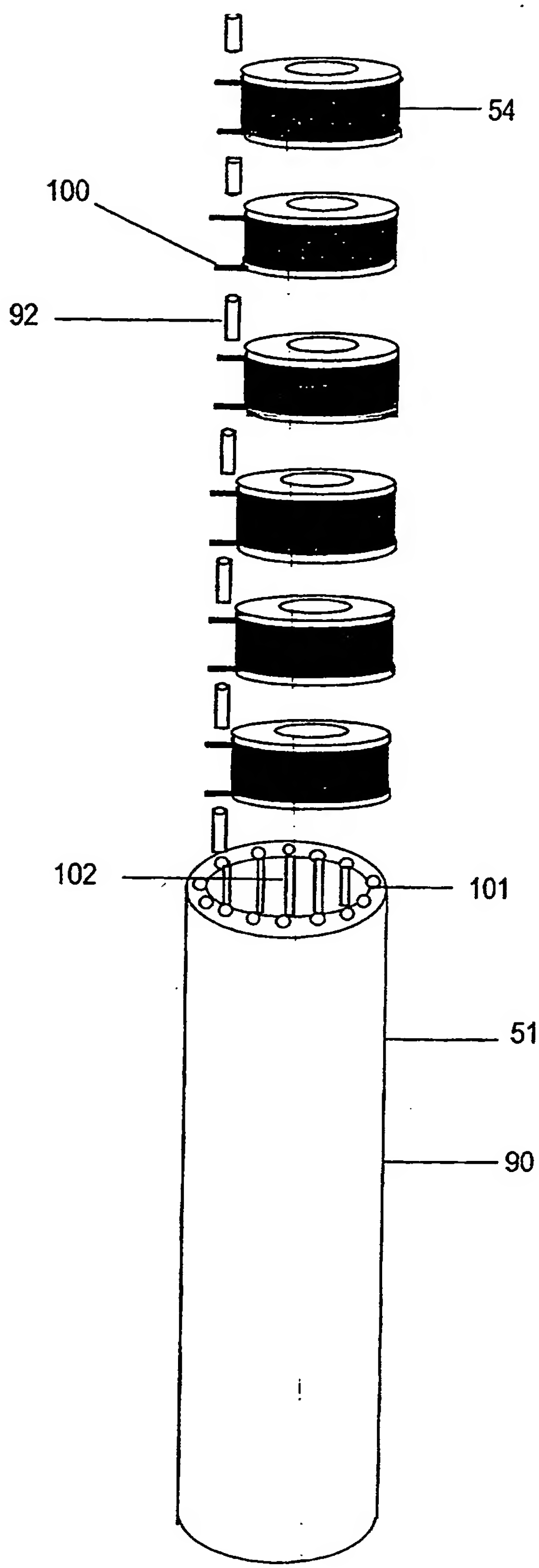
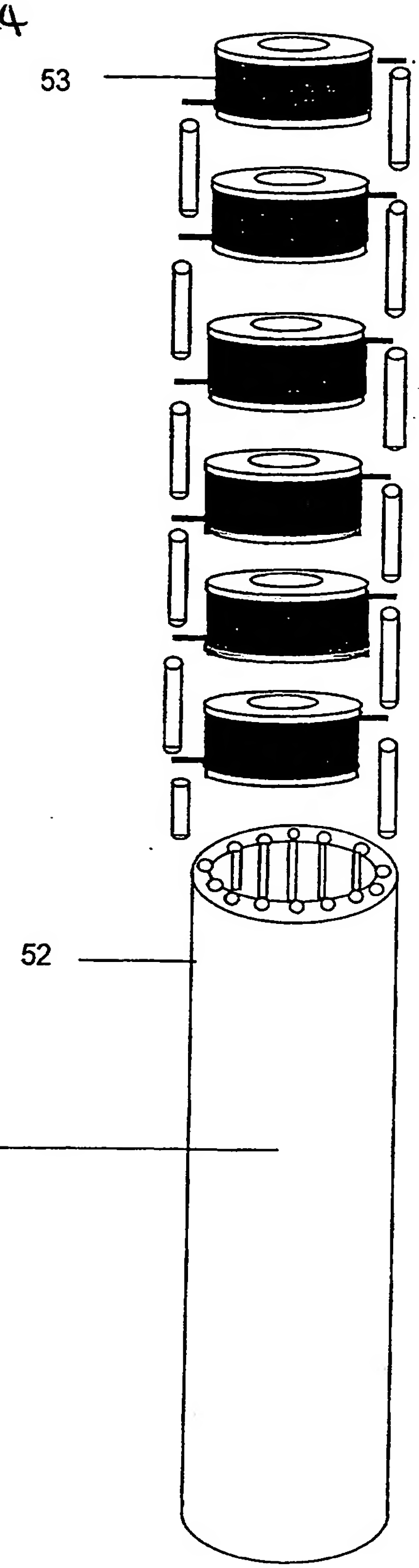


Fig. 7a



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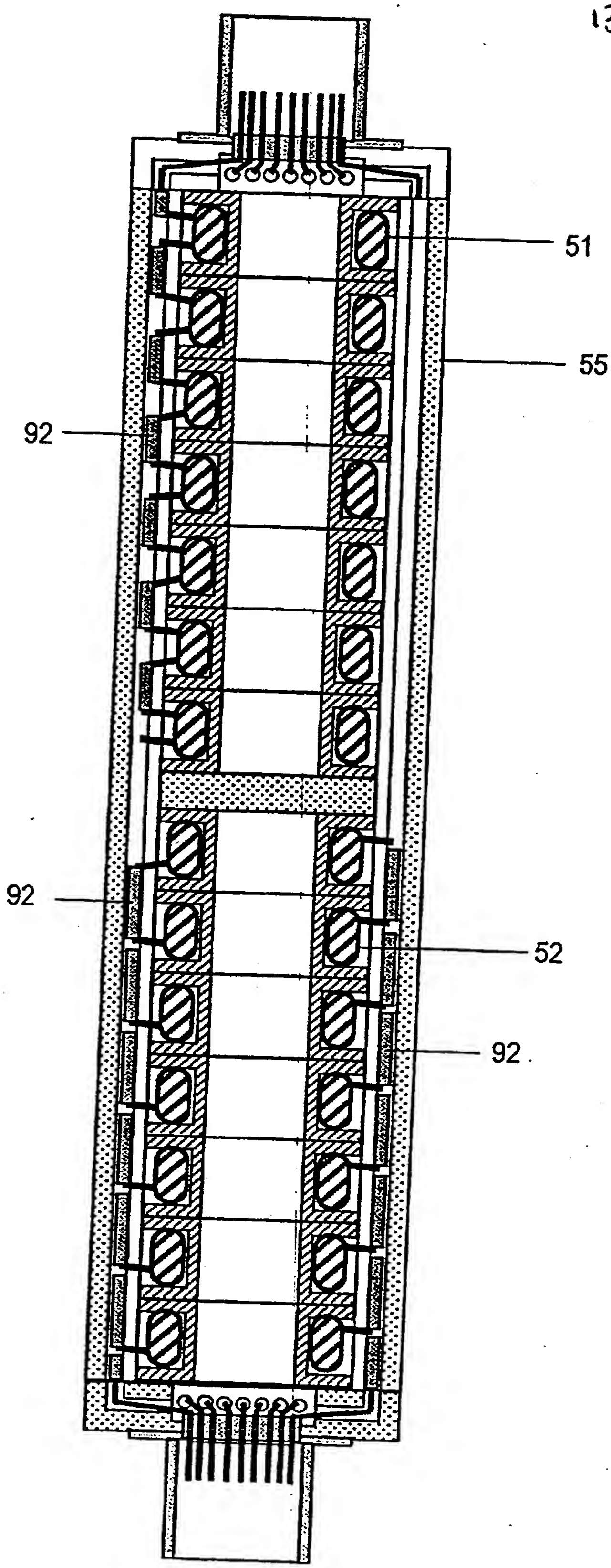

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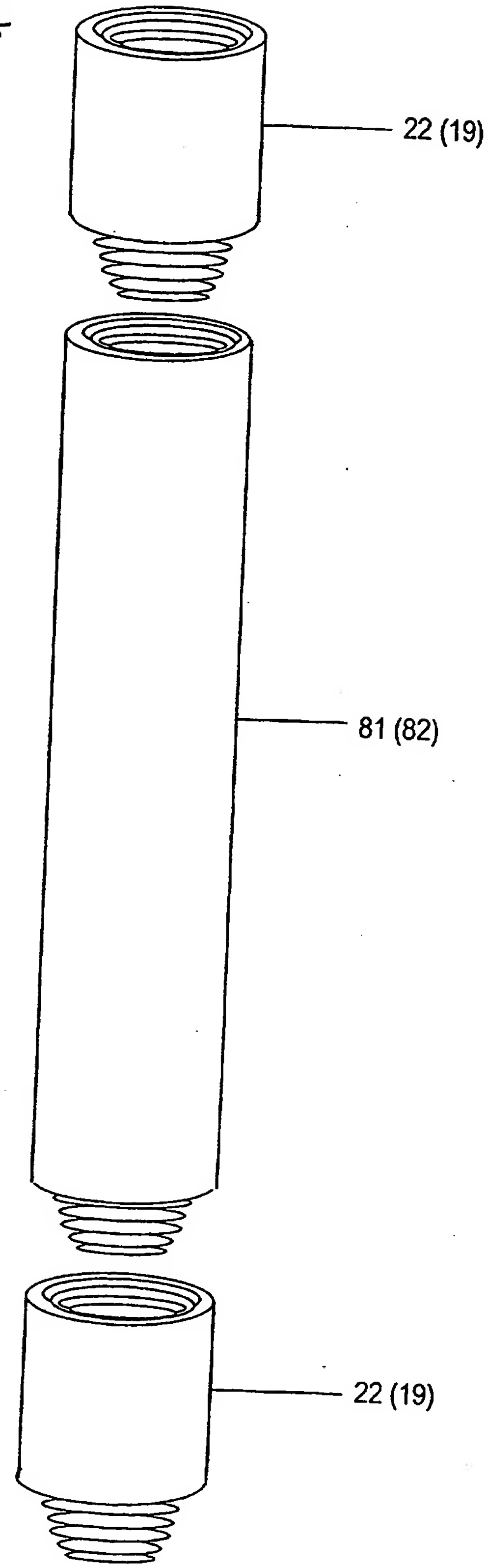

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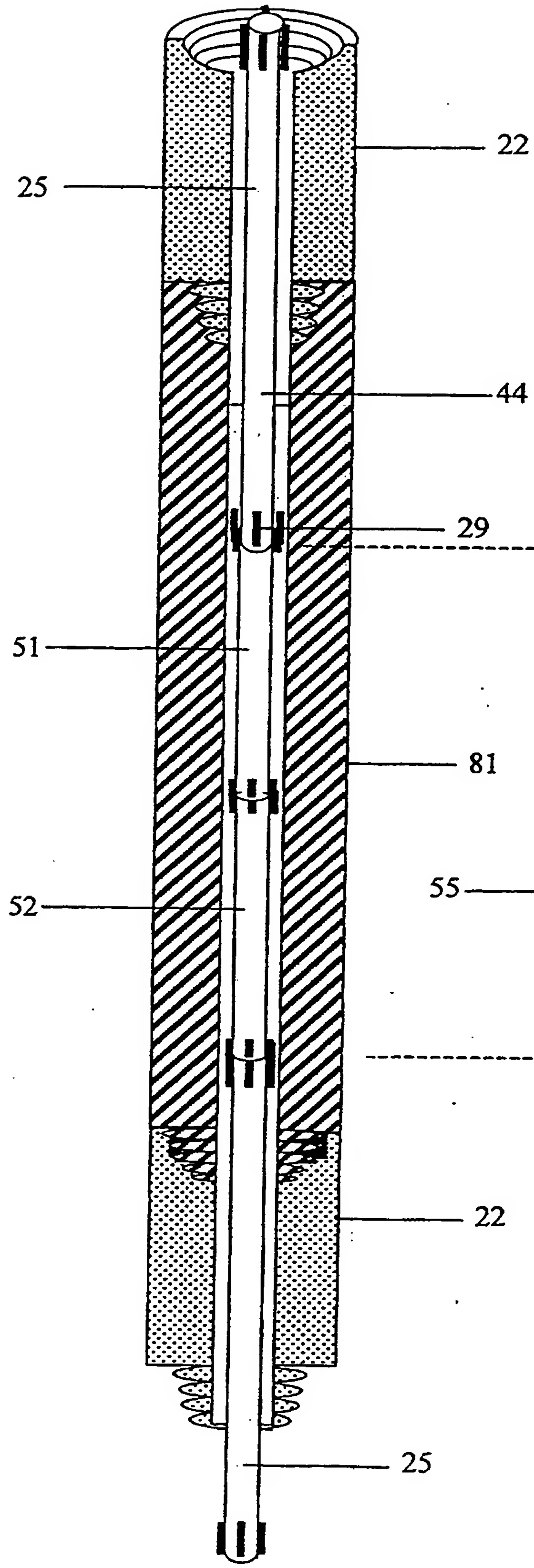
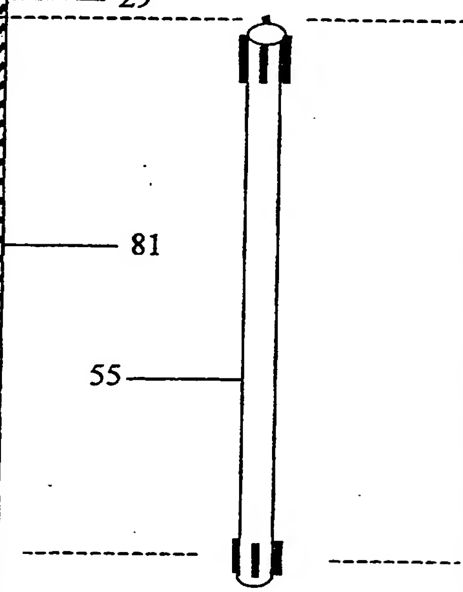


Fig. 7e



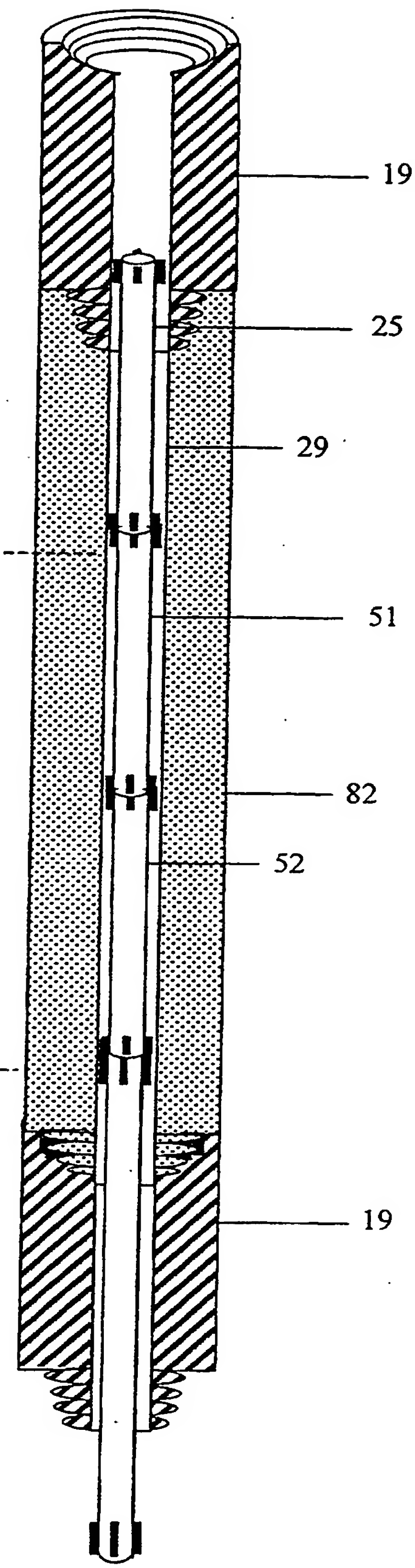


Fig. 7f

15/24

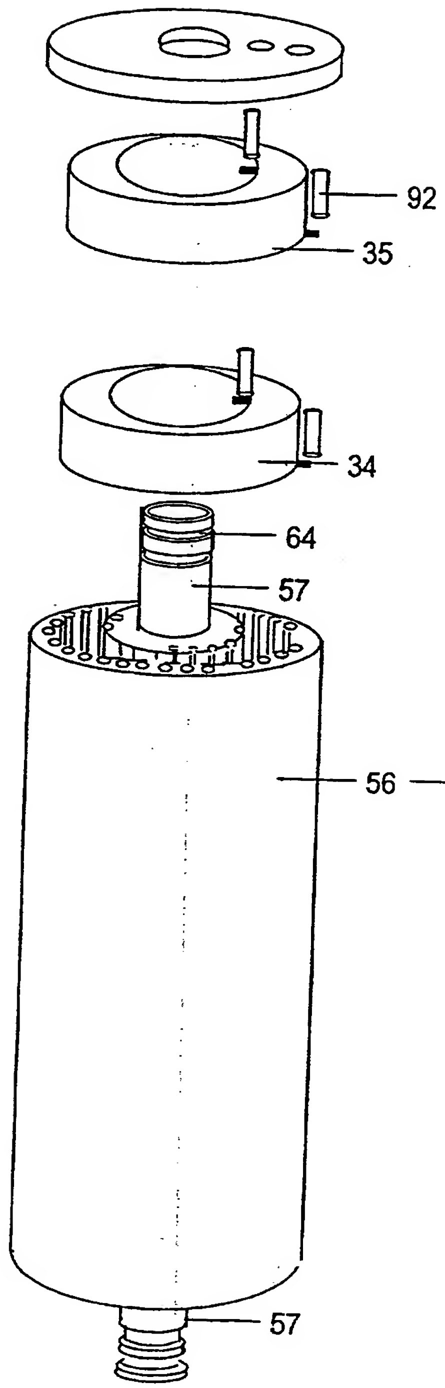


Fig. 8a

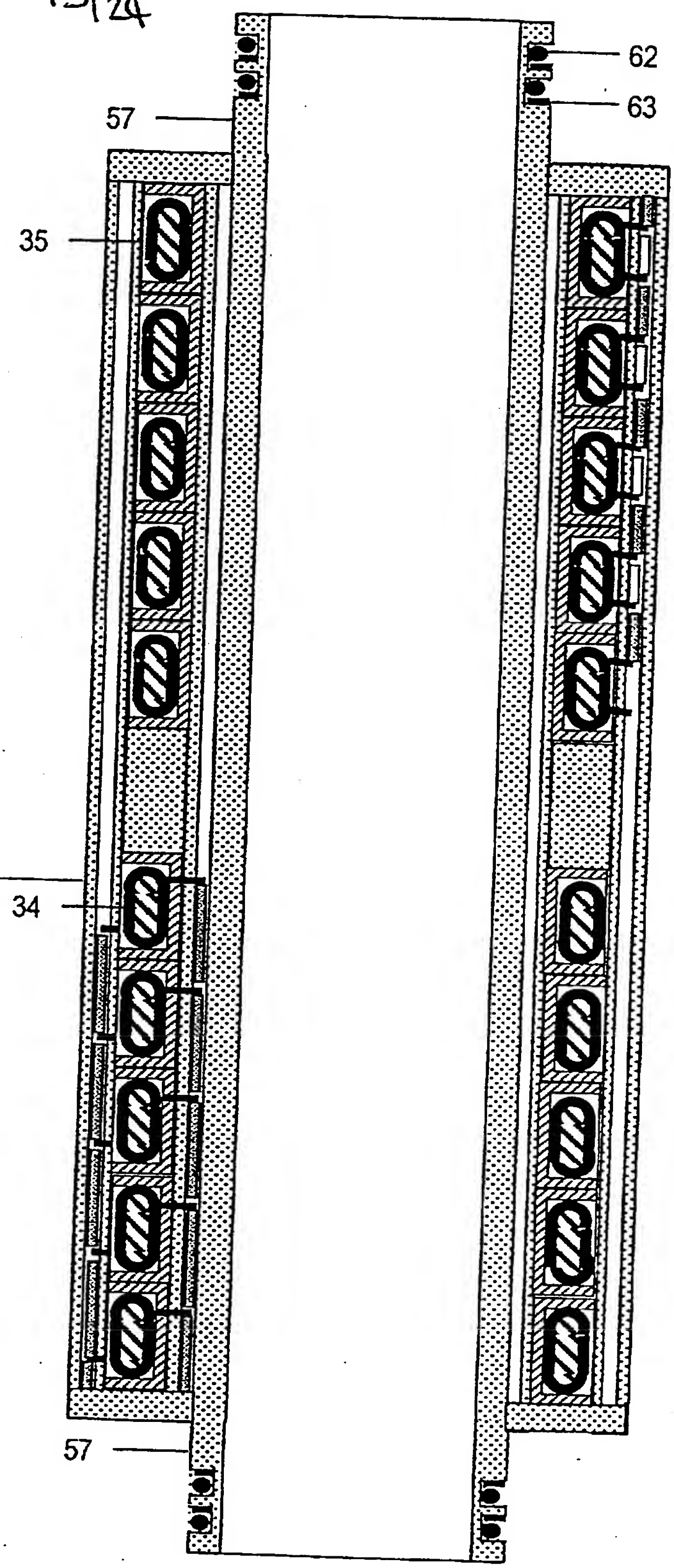


Fig. 8b

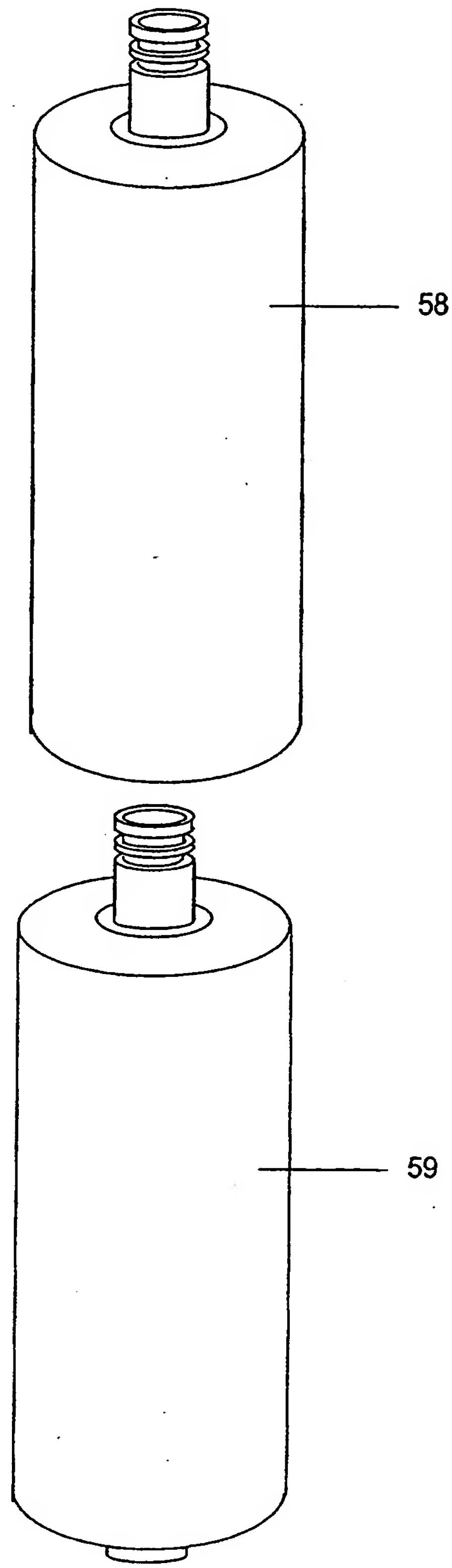


Fig. 8c

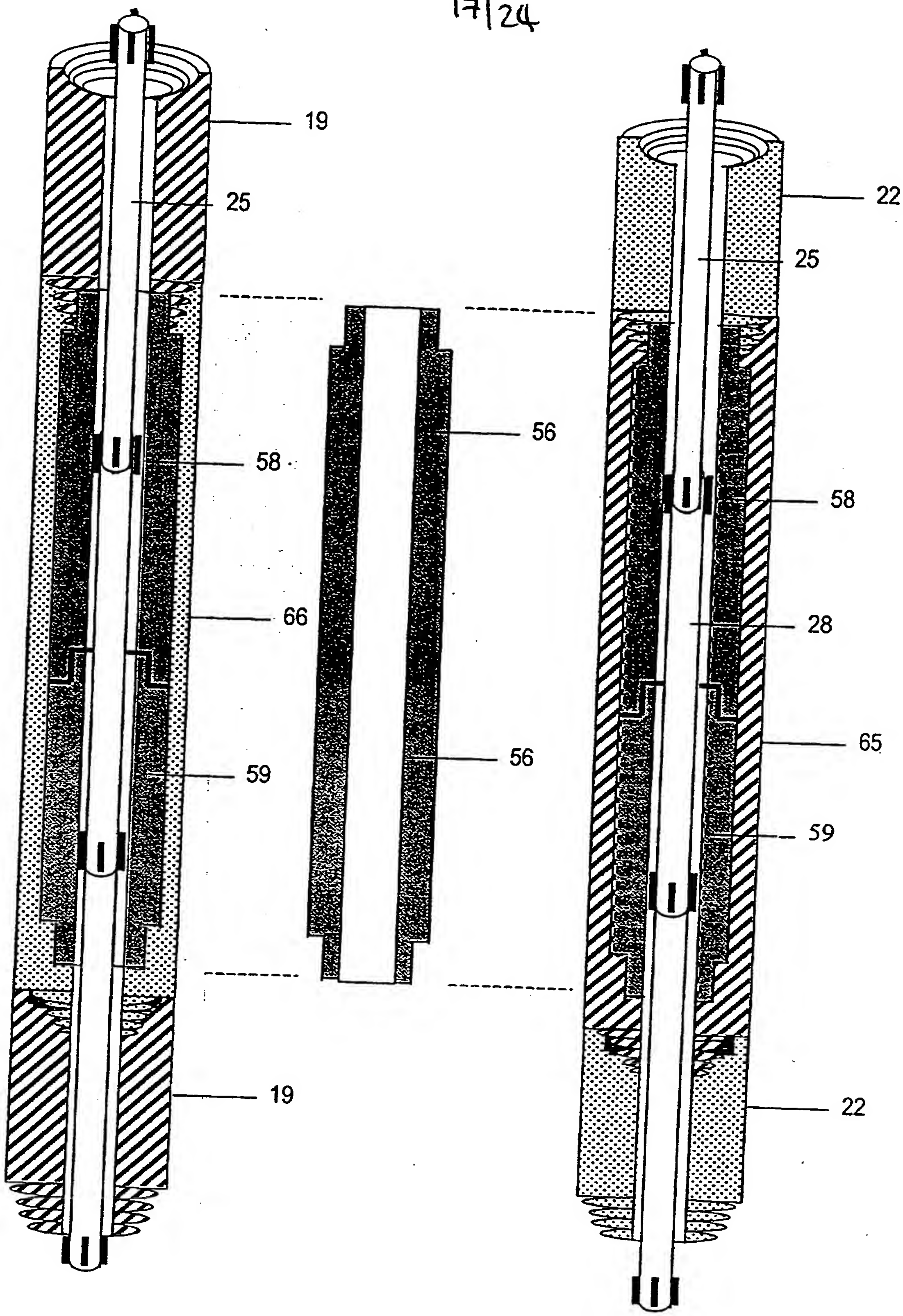


Fig. 8d

Fig. 8e

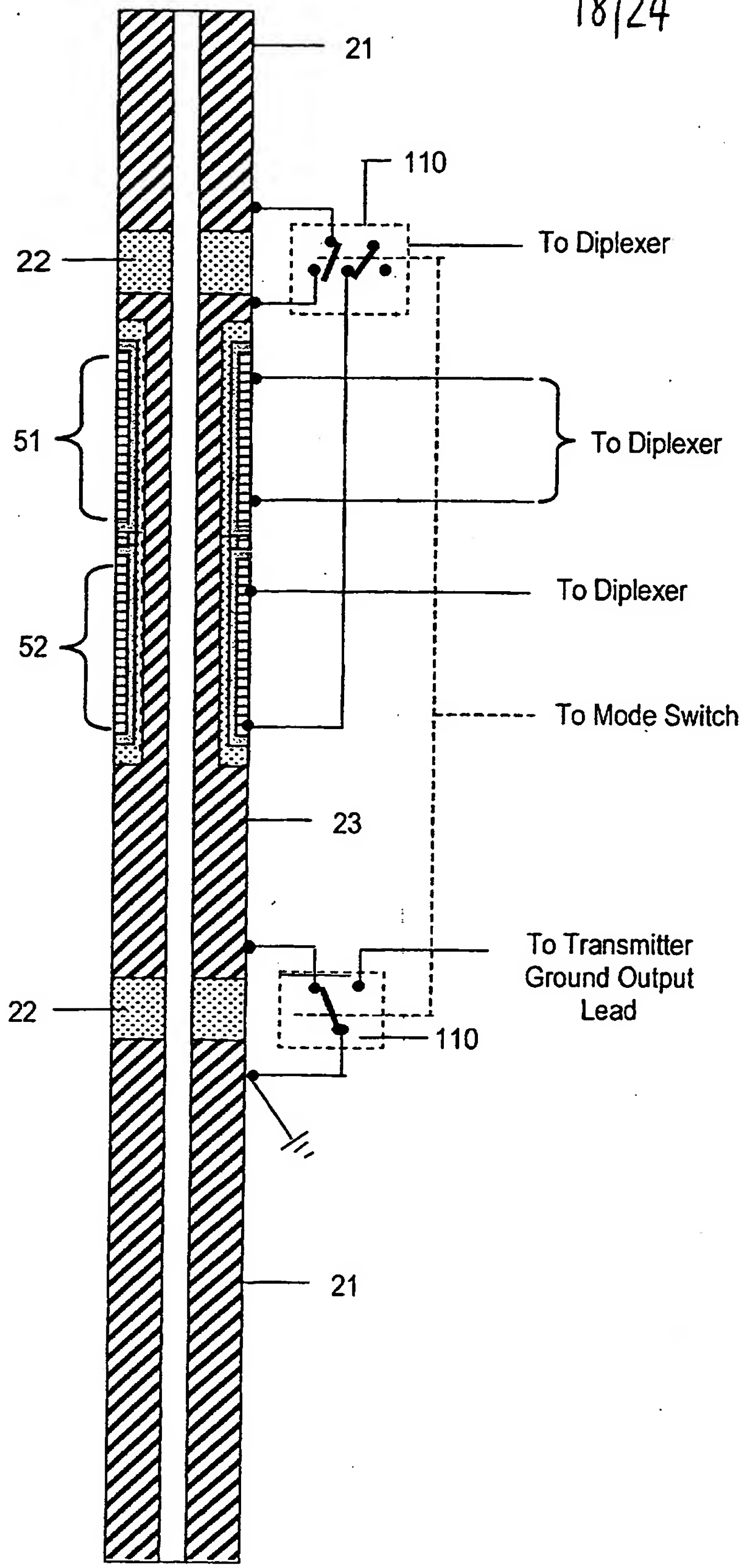


Fig. 9a

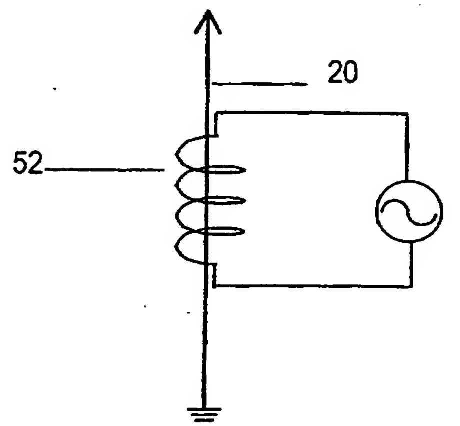


Fig. 9b

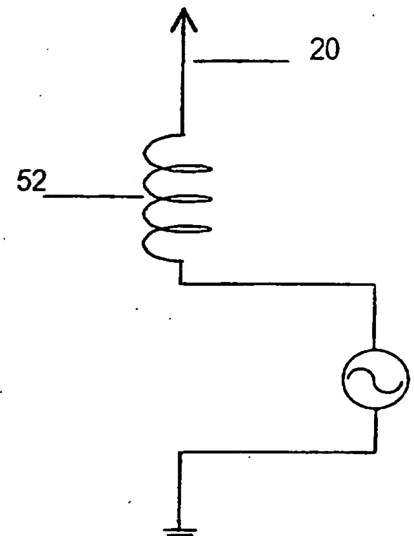


Fig. 9c

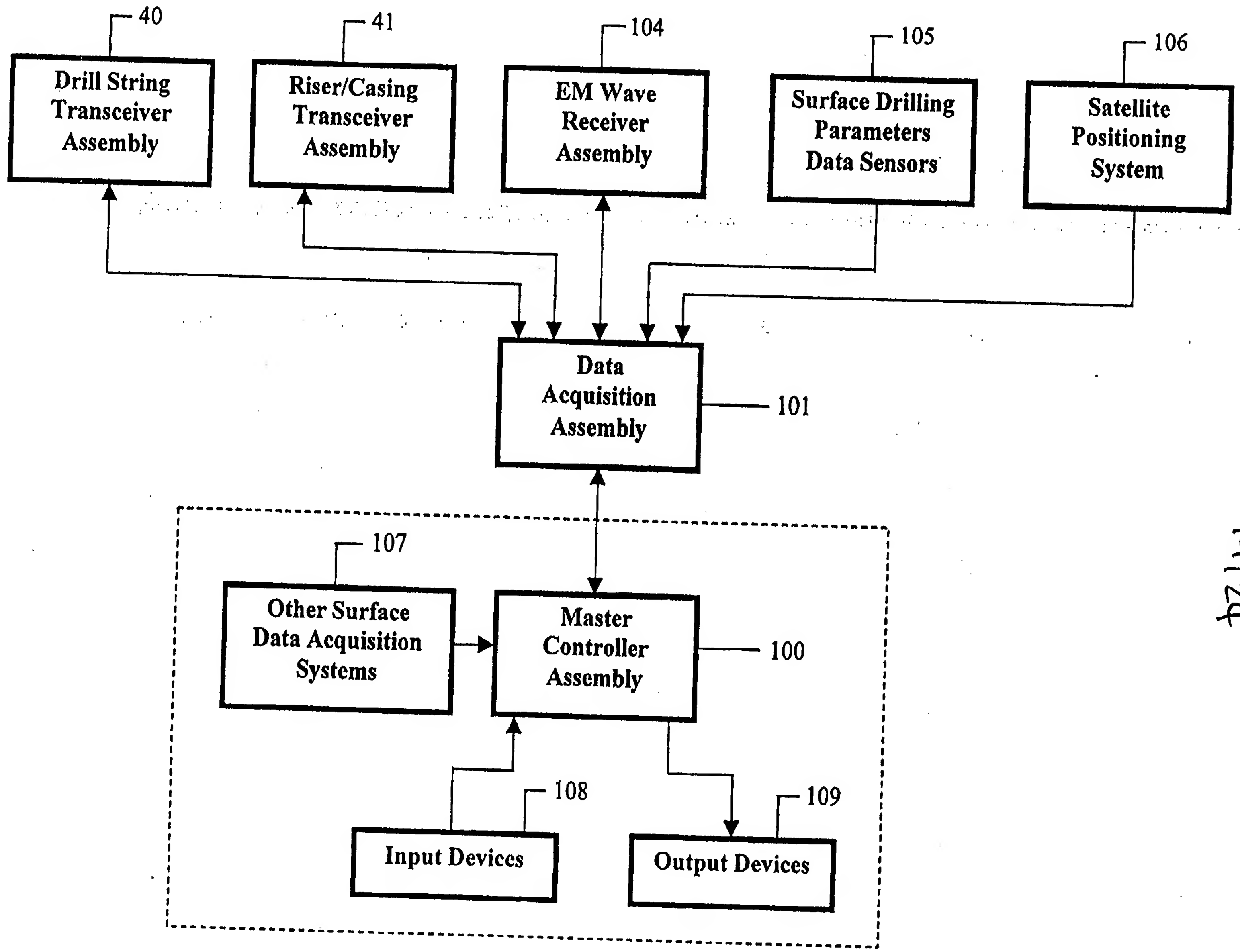
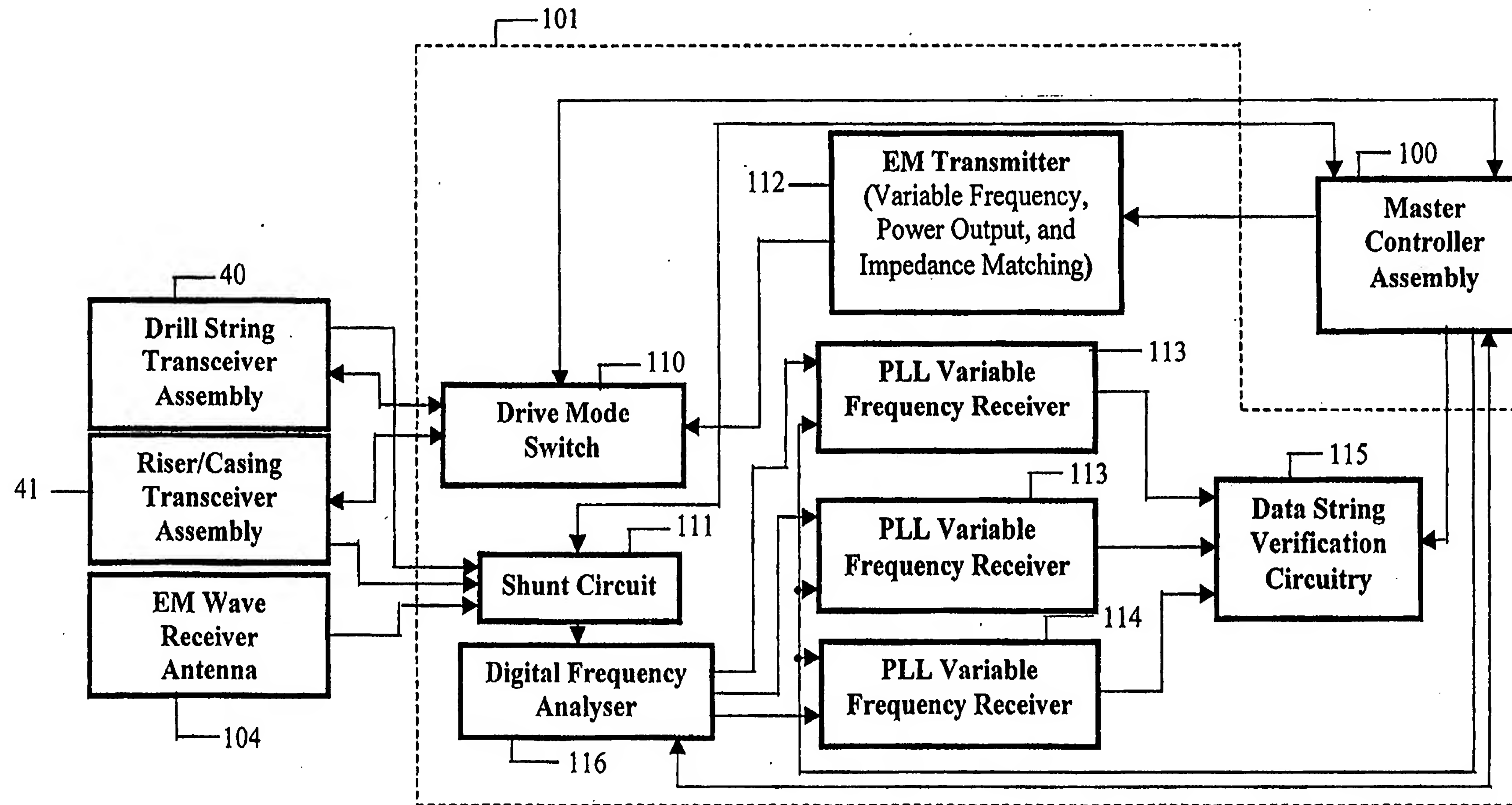

40
Drill String Transceiver Assembly
41
Riser/Casing Transceiver Assembly
104
EM Wave Receiver Assembly
105
Surface Drilling Parameters Data Sensors
106
Satellite Positioning System
Data Acquisition Assembly
101
107
Other Surface Data Acquisition Systems
Master Controller Assembly
100
108
Input Devices
109
Output Devices

Fig. 10a



101
Drill String Transceiver Assembly
40
Riser/Casing Transceiver Assembly
41
EM Wave Receiver Antenna
104
Drive Mode Switch
110
Shunt Circuit
111
Digital Frequency Analyser
116
EM Transmitter (Variable Frequency, Power Output, and Impedance Matching)
112
PLL Variable Frequency Receiver
113
PLL Variable Frequency Receiver
113
PLL Variable Frequency Receiver
114
Master Controller Assembly
100
Data String Verification Circuitry
115

Fig. 10b

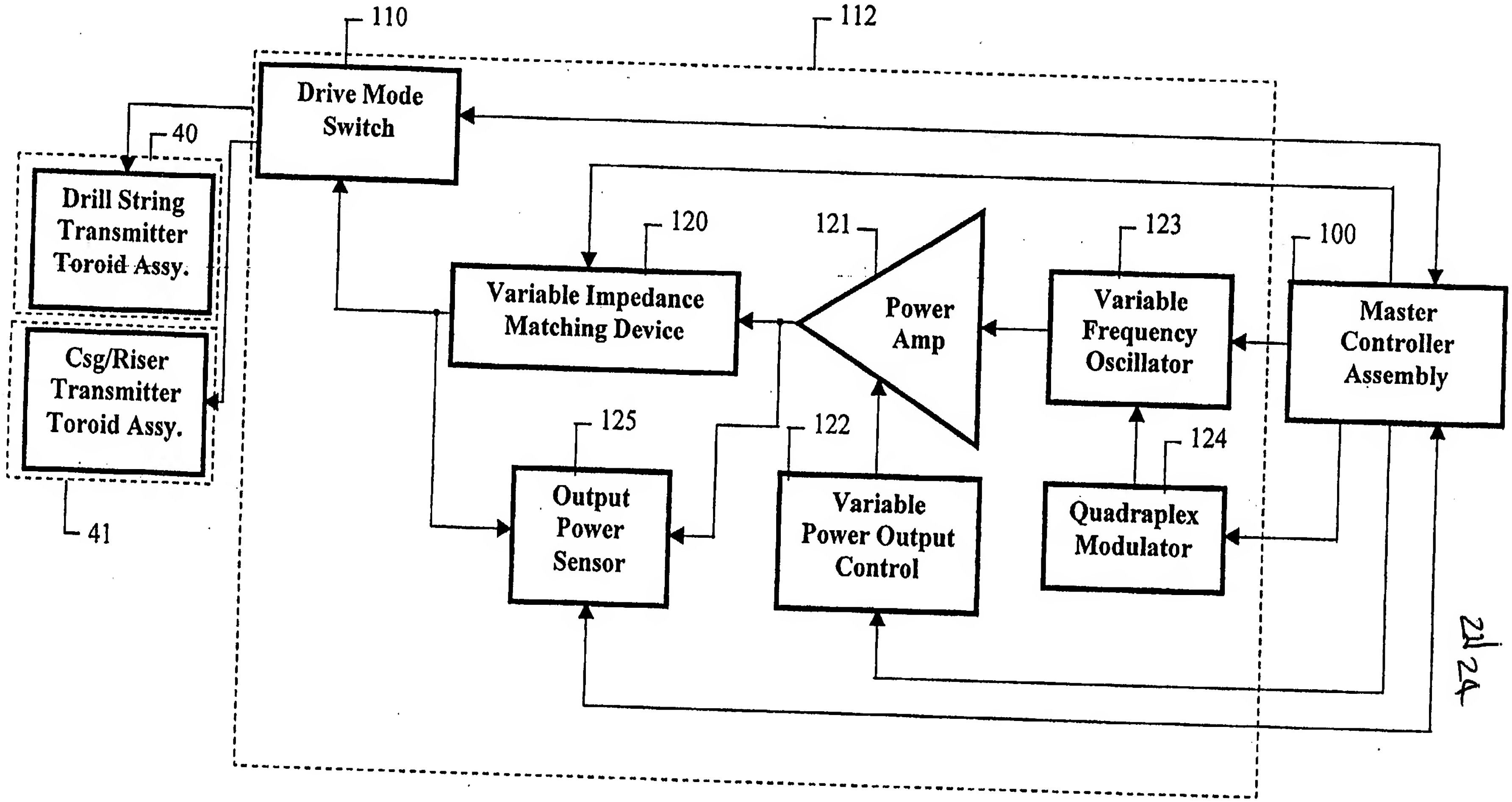

110
112
Drive Mode Switch
40
Drill String Transmitter Toroid Assy.
Csg/Riser Transmitter Toroid Assy.
41
120
Variable Impedance Matching Device
121
Power Amp
123
Variable Frequency Oscillator
100
Master Controller Assembly
125
Output Power Sensor
122
Variable Power Output Control
124
Quadraplex Modulator

Fig. 11

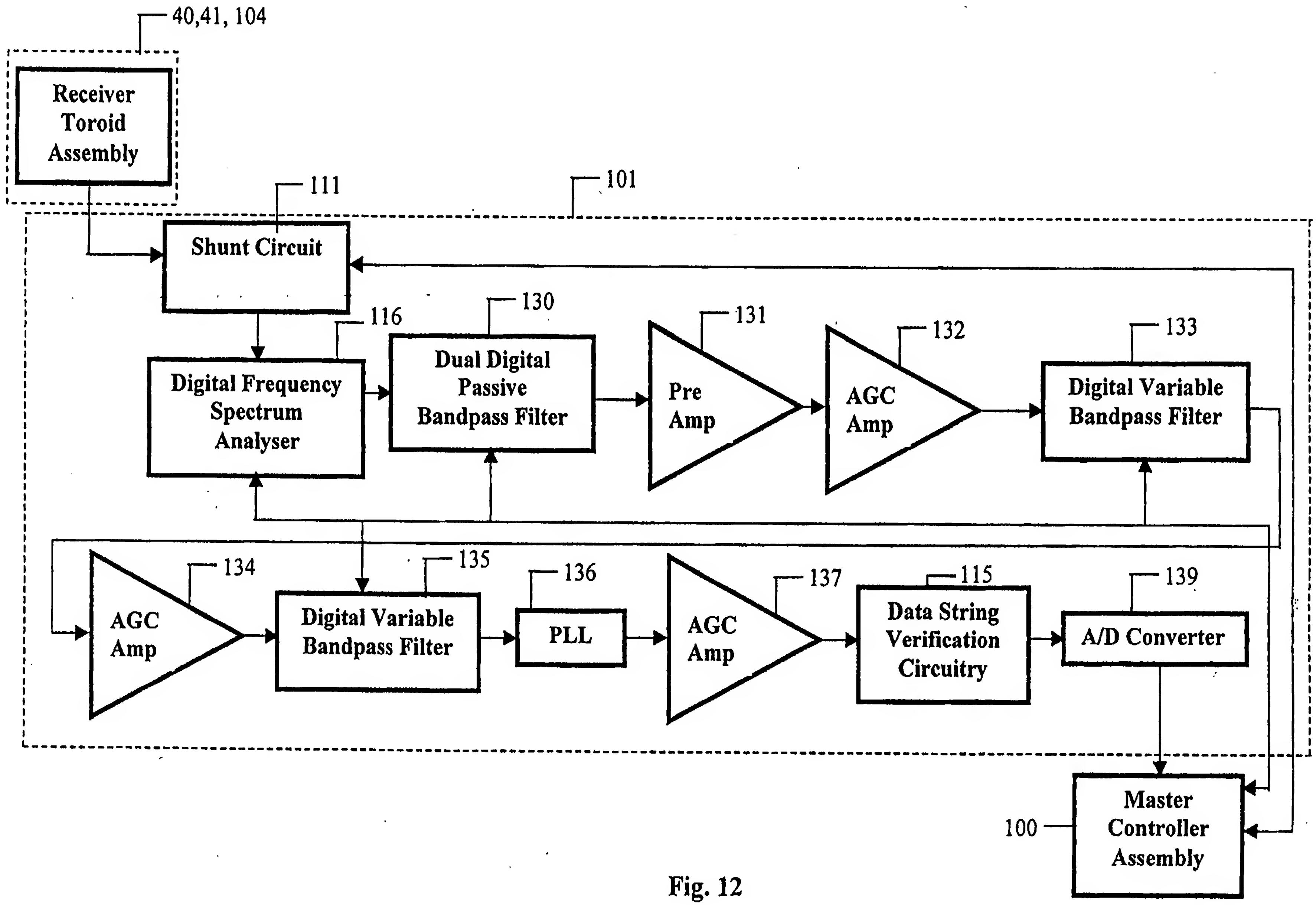

40,41, 104
Receiver Toroid Assembly
111
101
Shunt Circuit
116
130
131
132
133
Digital Frequency Spectrum Analyser
Dual Digital Passive Bandpass Filter
Pre Amp
AGC Amp
Digital Variable Bandpass Filter
134
135
136
137
115
139
AGC Amp
Digital Variable Bandpass Filter
PLL
AGC Amp
Data String Verification Circuitry
A/D Converter
100
Master Controller Assembly

Fig. 12

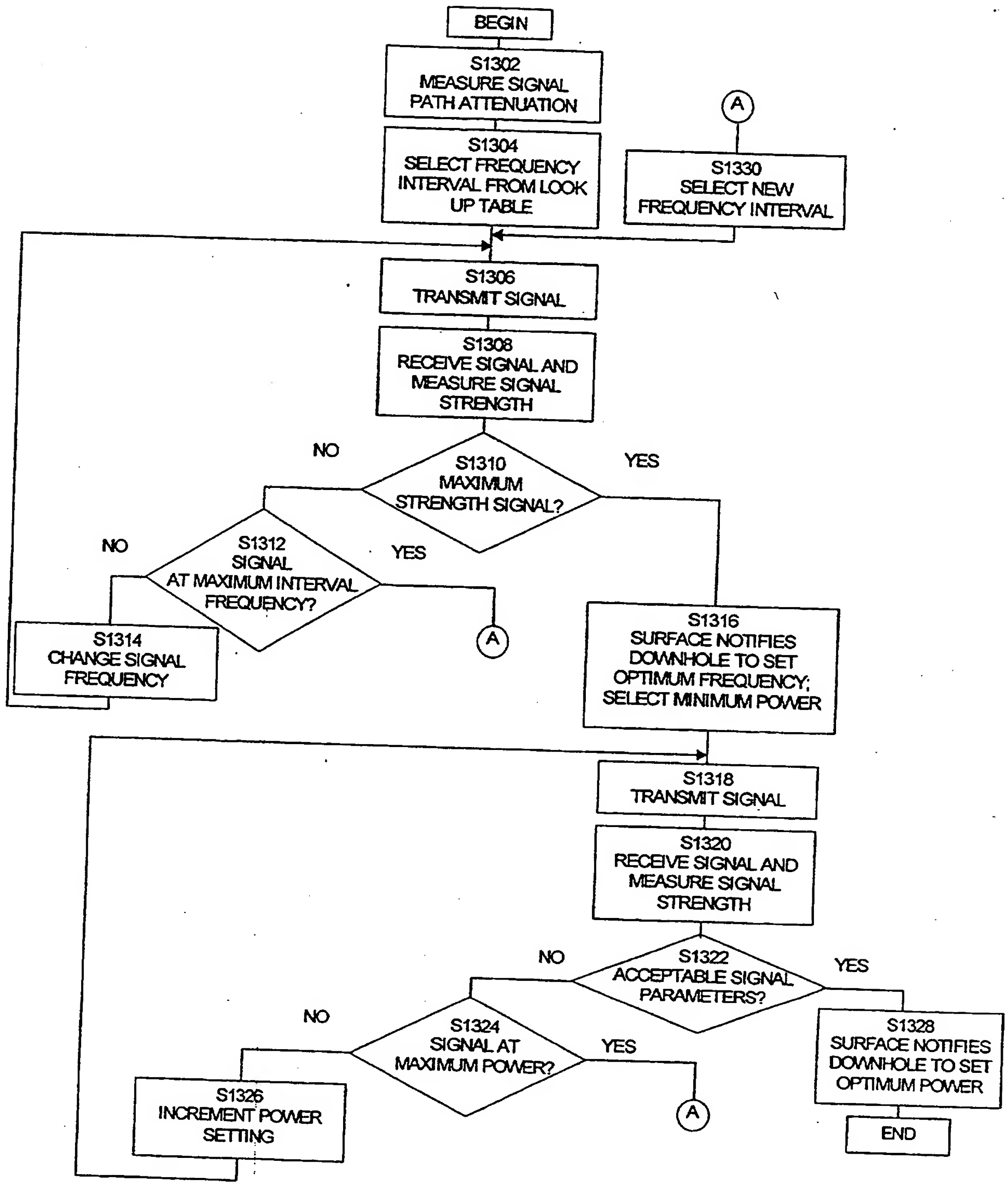

BEGIN
S1302 MEASURE SIGNAL PATH ATTENUATION
S1304 SELECT FREQUENCY INTERVAL FROM LOOK UP TABLE
A
S1330 SELECT NEW FREQUENCY INTERVAL
S1306 TRANSMIT SIGNAL
S1308 RECEIVE SIGNAL AND MEASURE SIGNAL STRENGTH
NO
S1310 MAXIMUM STRENGTH SIGNAL?
YES
NO
S1312 SIGNAL AT MAXIMUM INTERVAL FREQUENCY?
YES
S1314 CHANGE SIGNAL FREQUENCY
A
S1316 SURFACE NOTIFIES DOWNHOLE TO SET OPTIMUM FREQUENCY; SELECT MINIMUM POWER
S1318 TRANSMIT SIGNAL
S1320 RECEIVE SIGNAL AND MEASURE SIGNAL STRENGTH
NO
S1322 ACCEPTABLE SIGNAL PARAMETERS?
YES
NO
S1324 SIGNAL AT MAXIMUM POWER?
YES
S1326 INCREMENT POWER SETTING
A
S1328 SURFACE NOTIFIES DOWNHOLE TO SET OPTIMUM POWER
END

Fig. 13

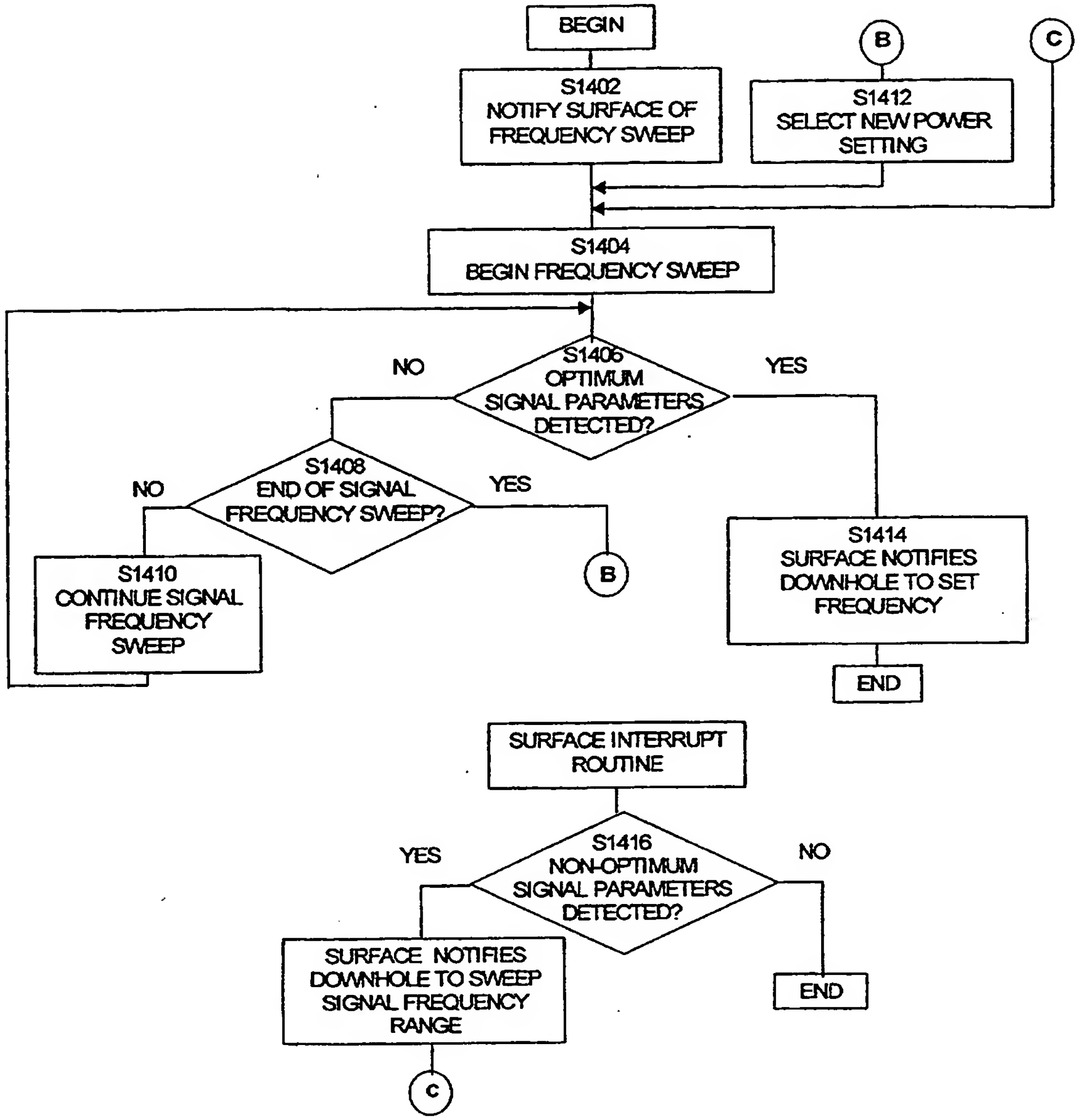

BEGIN
S1402
NOTIFY SURFACE OF FREQUENCY SWEEP
B
S1412
SELECT NEW POWER SETTING
C
S1404
BEGIN FREQUENCY SWEEP
NO
S1406
OPTIMUM SIGNAL PARAMETERS DETECTED?
YES
NO
S1408
END OF SIGNAL FREQUENCY SWEEP?
YES
S1410
CONTINUE SIGNAL FREQUENCY SWEEP
B
S1414
SURFACE NOTIFIES DOWNHOLE TO SET FREQUENCY
END
SURFACE INTERRUPT ROUTINE
YES
S1416
NON-OPTIMUM SIGNAL PARAMETERS DETECTED?
NO
SURFACE NOTIFIES DOWNHOLE TO SWEEP SIGNAL FREQUENCY RANGE
END
C

Fig. 14

2346509

APPARATUS AND METHOD FOR DOWNHOLE TELEMETRY

INTRODUCTION

This invention relates generally to telemetry systems for Measurement While Drilling (MWD) well logging systems.

Data about the type of and properties of geological formations being penetrated during drilling along with downhole drilling parameters and well bore direction is valuable to the petroleum industry. This data increases in value, particularly if the data can be obtained in real time during the drilling operations without having to remove the drill string from the bore hole. However, the downhole environment is extremely harsh including elevated temperatures, high pressures, and severe shock and vibrations. Drilling fluids are also highly abrasive.

Systems capable of providing such real time data are typically referred to as "MWD" or Measurement-While-Drilling well logging tools and are serially incorporated into a drill string above the drill bit. The system when applied to a borehole may be used at any time during the drilling of the borehole but is primarily used in providing real time transmission of large quantities of data gathered near the bit simultaneously while drilling. A data telemetry or telecommunications link capable of transmitting data from down-hole to ground surface instrumentation and capable of transmitting control data from ground surface to down-hole instruments is the heart of any MWD well logging tool.

The measurement while drilling concept offers substantial incentives. This concept will allow safer, more efficient, and more economical drilling of both exploration and production wells.

The majority of systems in use at the present time use positive or negative pressure pulses in the drilling fluid to transmit data from the drilling location to the surface. This provides a very low data rate (generally up to eight bits per second).

In US 2,354,887, US 2,389,241, and US 2,411,696, Silverman describes proposed MWD systems for collecting and transmitting data utilising the drill string

and either toroidal transformers or insulated electrodes to induce electromagnetic currents in underground formations for both data collection and "well signalling". In US 3,793,632 and US 4,302,757, Still discloses methods utilising the drill string for data transmission with low frequency electromagnetic waves induced by toroidal transformers (virtual electrodes). Other electromagnetic wave transmission systems for establishing a data/control telemetry link between ground surface and down-hole instrumentation are described in: US 4,087,781, Grossi et al; US 4,348,672, Givler; and US 4,578,675, US 4,630,243, and US 4,739,325, MacLeod. MacLeod refers further to documents US 4,181,014, Zuvela et al; US 4,087,781, Scherbatskoy; US 3,967,201, Rorden. The theoretical basis of utilising a drill string as an element for inducing electromagnetic waves or currents to communicate measurements from underground has been presented by J.R. Wait and D. A. Hill, in an article entitled "Theory of Transmission of Electromagnetic Waves Along a Drill Rod in Conducting Rock" *IEEE Trans. on Geoscience Electronics,* Vol. GE-17, No. 2, (5/79); and by K. Lee & G. Smith in an article entitled "Measured Properties of Bare and Insulated Antennas in Sand", *IEEE Trans. of Antennas & Properties,* Vol. AP-23, No. 5, (9/75) pp. 664-670, employing a Hertzian dipole.

Many different types of electromagnetic wave (EM) telemetry systems have been proposed, postulated and even tried for MWD logging tools. There are two known commercially operating systems in use as of this time but these are only capable of operation on land based drilling sites. From the literature it is apparent that many of such EM telemetry systems would work if the conducting environment were homogeneous, and undifferentiated.

However, the operating environment is quite differentiated and inhomogeneous. This is caused by the constantly varying electrical properties of the drill string, drilling fluid, earth's geological strata, and in the case of offshore locations, the water properties. The drill string properties vary with length, type of drilling fluid used and downhole temperature gradients. The drilling fluid properties vary with types of additives used for increasing the mud weight or improving lubrication qualities, and the downhole temperature gradient. The earth's strata vary with composition, depth, local, and the sequence and spacing of the different

formations. The water's electrical properties vary with temperature and salinity among other things.

In summary, an EM data/control telemetry system linking an MWD logging tool to ground surface must not only survive elevated temperatures, high pressures, severe vibrations and abrasions, it must be able to adapt and function in a constantly varying electrical environment. For sub-sea drilling operations, there is the additional burden of the sea-water surrounding the riser pipe, over perhaps 1000 metres below the rig.

None of the prior references appears to address the specific problems associated with borehole telemetry offhore. The distances achievable by the prior techniques are also found to be extremely limited. One reason for this is the exponential fall-off in signal strength, with increasing distance from the transmitting device down-hole, coupled with the limited power and size of the down-hole modules. MacLeod, for example, proposes repeater stations along the drill string, as a solution to this problem MacLeod also proposes that a pick-up toroid should be placed down-hole, at the foot of the casing. In this way, signals need only be communicated the length of the un-cased borehole. On the other hand, the toroid cannot be recovered from such a position, and the provision of suitable cabling from the foot of the casing to the surface brings significant problems. In fact, the present inventors have recognised that, once the signal reaches the casing, it has a relatively smooth conduction path to the surface. Accordingly, it is possible to pick up the signal from the casing at the surface end, instead of or in addition to pick-up from the drill string itself.

The main aim of the invention is to provide a high rate borehole data acquisition and communication system, operating in real time and able to dynamically adjust its transmission and reception parameters in accordance to changing environmental parameters. A particular aim is to provide a system capable of use in offshore drilling situations, where known systems fail to operate.

According to one embodiment, the invention provides a very low frequency (VLF) high data rate EM two-way telemetry system that links down-hole instrument measurements with a surface data acquisition system. The system contains both

down-hole and surface central microprocessor units that continuously monitor their own electrical environment and communicate this data to the other. The central microprocessor units continuously monitor the conductivity of the transmission medium and adjust the transmitter and receiver parameters to the constantly changing electrical environment in which it is operating. The system uses this data to optimise the frequency, power output requirement, impedance matching and coupling requirement, and type of drive system required to allow high data rate reception between the two units. The data transfer system operates via the drill string, casing and conductor/riser pipe, or the surrounding strata and/or water, or all of these in parallel. The system generates the optimum required carrier frequency, adjusts to the required power output, selects proper impedance matching, coupling type and drive type, and digitally quadra-phase shift modulates the carrier frequency with the data signals.

In the particular embodiments described, the invention provides a selectable, dual-mode of EM telemetry, using a toroid assembly that is either electrically connected to induce signal flow in the conductive medium, or connected to form a Hertzian dipole antenna for data transmission toroid-coupled data transmission system wherein the normal functioning of a conventional drill collar is not disturbed. A scheme utilising multiple toroids is used in the embodiments, instead of a single toroid, which brings particular advantages. The power required for a multiple toroid telemetry system is far less than that of a single toroid system. The power that can be coupled into the drill string is higher, without saturating the toroid core. Utilising a number of small toroids result in an increase in system performance over large single toroid systems. The impedance matching necessary in such a telemetry system is also much simplified.

Another advantage of this scheme is the increased depth over which telemetry can be carried out with communication achievable over depths of six to ten km.

A first aspect of the invention, aims to provide a novel toroidal coupled data transmission system wherein the toroid assembly is provided with an electrical isolation system, to prevent short circuiting the secondary of the data transmission system (the remaining drill string), which is highly rugged and practical for sustained

downhole operation. Various specific configurations are disclosed in the embodiments described below.

A second aspect of the invention aims to provide a novel toroid assembly for the transmit and/or receive toroids which will allow transmission of data signals through the drill pipe, the earth's strata, through water (if operating in an offshore environment), and the atmosphere, either at the same time, or switchably.

A third aspect of the invention aims to provide borehole data acquisition tools with an adjustable parameter electromagnetic wave communication link between down-hole measurement units and surface data acquisition units for optimisation of the data reception rate of the system.

A fourth aspect of the invention aims to provide a multiple signal reception system that will receive both the current signals transmitted via the drill string, casing and conductor/riser pipe and the electromagnetic waves propagated through the earth's strata, water (if offshore location) and the atmosphere. In the embodiments disclosed, microprocessor controlled receiver units will compare the two signals to ensure that all data bits are received, to select the signal that contains all data bits for processing and/or to merge the two signals to create a total bit data chain for processing thus optimising the quality of reception. In the embodiments disclosed, three different means of transmission reception are deployed in parallel.

A fifth aspect of the invention aims to provide a selectable dual transmitter drive system controlled for example by a central microprocessor control unit. In certain of the embodiments disclosed, an electronic switch is provided for changing from a toroidal coupled telemetry system to a dipole transmission system for optimising data transmission and reception in different environmental conditions.

A sixth aspect of the invention aims to provide a downhole telemetry system of which the majority of its components can be retrieved from down-hole, via a wire-line retrieval tool through the internal bore of the drill string in the event of a total down-hole system failure or if the drill string becomes stuck in the well bore and cannot be retrieved.

These and other aspects of the invention, which will hereinafter become more apparent, are each embodied in one or more of the embodiments described below by providing an Integrated Borehole Information System (IBIS ™), comprising a

modular constructed down-hole system and a surface data acquisition and control unit. The down-hole system is contained within a drill collar at the end of the drill string and above the drill bit. The down-hole system consists of a power module, communication module, central electronics module and various drilling parameters and formation evaluation sensor modules.

Included in the down-hole system are two multi-toroid assemblies coaxial to the drill collar and the borehole in the surrounding strata.

In accordance with a seventh aspect of the invention, a transmitting toroid assembly consists of a number of individual drive connected in parallel to reduce the coupling losses and increase the current limits of the individual coils. The coils may each be wound to make a non-resonant system.

In accordance with an eighth aspect of the invention, a receiving toroid assembly consists of a number of individual receiver toroid coils connected in series. The coils may each be wound to make a non-resonant system.

As an alternative, or in addition to the use of series/parallel toroid assemblies, capacitive tuning may alleviate the voltage, current and magnetic flux requirements mecessary to couple sufficient power into the drill string.

The individual driver and/or receiver individual toroids may be mounted on screens to reduce the capacitive coupling between the toroids and the drill collar.

In accordance with a ninth aspect of the invention, toroid assemblies for borehole telemetry are electrically isolated from different sections of the drill collar by electrically insulating sub-assemblies ("subs") or gaps located above and below the assemblies which maintain a significant potential difference between different sections of the drill collar.

The down-hole system is powered in the embodiments by the power module which contains a turbine/alternator (primary power source), voltage and frequency conditioning circuitry, battery charger and battery pack (secondary power source). The turbine/alternator is powered by the flow of drilling fluid through the bore of the drill string. The electrical output of the alternator is conditioned by a power supply and distributed to the various modules in the down-hole system. Battery back-up may be provided, to maintain communication when drilling fluid is not flowing.

The communication module in one embodiment contains the VLF EM transmitter and receiver, drive switching circuitry, and impedance and conductivity measuring circuitry. A central electronics module controls the functions of the communication module.

The central electronics module contains the master microprocessor that functions as the command and control centre for the downhole tool. The processor calls up data for transmission from the measurement modules, in a pre-programmed sequence or on instructions from the surface system, codes the data, and sends it to the transmitter section of the communication module. The master processor also monitors the operating parameters of the other system modules and stores this data in memory to be retrieved when the system returns to the surface. The processor notifies the surface system when there is a malfunction in any of the system modules.

As the system's operating environment is inhomogeneous the telemetry signal path's electrical parameters are continuously changing. These changes are due but not limited to such factors as increased drilling depth and changes in the electrical properties of the formation (geological stratum), the drill string and/or the drilling fluid. The length of drill string below the transmit toroid assembly may change from run to run. The central electronics module continuously monitors the signal amplitude and signal-to-noise ratio that indicates the changes. The module also monitors the receiver for transmitted data from the surface system.

When the signal amplitude and/or the signal-to-noise ratio reach levels that would cause a reduction in data reception the module can adjust the transmitter operating parameters to optimise signal reception. The module can adjust the telemetry system carrier frequency, transmitter power output, transmitter drive mode (inductive or dipole), and transmitter drive impedance, or any combination of these parameters depending on which parameters in the telemetry signal path are affecting these levels, to optimise transmission.

The central electronics module determines which parameters of the communication system require changing to optimise the telemetry process by measuring the signal current attenuation and the drive impedance of the telemetry system. Where a current induced in the drill string is detected at the surface, the system measures the current attenuation of the telemetry path by comparing the

surface receiver toroid or other assembly output voltage to a fixed down-hole transmitter toroid assembly input voltage.

In accordance with a tenth aspect of the invention, the telemetry path drive impedance may be measured by comparing the down-hole receiver toroid assembly output voltage to fixed drive conditions (i.e. carrier frequency and output voltage) of the adjacent transmitter toroid assembly. EM telemetry can be accomplished for example by either an induction type drive system or a vertical Hertzian dipole system. The invention can be implemented using either system.

The central electronics module in one embodiment selects the type of transmitter drive system to be used and electronically switches the transmitter toroid assembly from an induction drive method to a vertical dipole method.

Sensor modules may be included to measure and process the data for such parameters as directional, shock and vibration, weight and torque-at-the bit, internal and annular temperature, annular pressure, internal and annular fluid flow, formation resistivity and gamma ray properties as well as hole diameter, formation density and porosity, etc. The sensor modules in the preferred embodiment are stand-alone modules that contain a power supply, analogue to digital converters, microprocessor and the necessary control circuitry for proper operation on their own. The modules are of the "smart" design, that is each module is pre-programmed with the calibration and correction data for the specific sensors it monitors to allow the package to correct the raw sensor readings before sending the data to the main electronics module for coding and transmission. This reduces the amount of data to be sent to the surface thus allowing more sensor measurements to be transmitted in less time. This efficient coding, together with the higher data rates available relative to mud pulsing telemetry, allows data not previously available to be transmitted. Thus, for example, a safety module might monitor for early signs of gas, allowing operators to avoid a dangerous blow-out.

The modules may be designed so that they can be run in any number or sequence without affecting the overall system operation. The modules may be programmed to identify themselves to the central electronics module when the system is initially powered up so it knows what modules it has control of.

The surface data acquisition and control system in the embodiments comprises microprocessors, transmitter and receiver, antenna systems, interface circuitry, visual display units, and data recorders. The system receives the transmission signal from the downhole system, processes and decodes it, and outputs the received data to specific displays and data recorder and storage units in formats useable by the operator.

The surface data acquisition system controls the total system operation via pre-programmed formats or operator input instructions. The surface system also constantly monitors the surface electrical environment and communicates the data to the downhole system to optimise the transmission parameters (signal to noise ratio), as described in more detail below.

In implementing the fourth aspect of the invention as set forth above, the surface system in the disclosed embodiments uses three antenna systems for the reception and transmission of data. Two of the systems function for both data transmission and reception while the third antenna system is primarily for data reception. The first two systems each comprise a transmitter toroid assembly and a receiver toroid assembly. One of the antenna systems is positioned around the drill pipe at the surface and the other system is positioned around the conductor pipe or riser at the surface. The two systems communicate with the downhole system via current flow transmission in the drill pipe and the well casing. Due to the mechanical and electrical properties of the conducting medium, at times there is less signal attenuation caused by the well casing than the drill pipe. At such times, signal propagation is more efficient in the casing than the drill pipe so both systems are used.

In accordance with a further aspect of the invention, the pick-up of signals from the top of the casing or riser, whether by toroidal transformer or other means, can be used beneficially independently of the other features of the system.

The third antenna system consists of a horizontal dipole antenna for the reception of the electromagnetic waves produced by the system. These waves propagate from the transmit toroid assembly into the surrounding strata, water (if at an offshore location), and into the atmosphere. These waves induce current flow in the antenna and are processed by the surface system.

The surface system in such an embodiment contains the circuitry to receive all three antenna system inputs, compare the data train to ensure that all data is received by one, two, or all three of the antenna systems, plus circuitry to amplify, decode, log and display the data. If no one antenna system receives a complete data train, due to electrical noise or signal attenuation, the surface system can combine the three data trains to produce a complete data train.

One primary advantage of the novel transmission system is that it allows data reception rates higher than other systems. Another advantage is that the transmission system monitors the varying electrical parameters of the inhomogeneous conducting environment and adjusts its operating parameters to optimise the signal to noise ratio.

A further advantage is that the system makes use of both types of waves produced in the propagation of electromagnetic waves in ensure reception of a complete data train.

Still another advantage is that it provides a (relatively) high data rate two-way communication system between downhole measurement devices and surface systems to provide real time information of down-hole conditions during the drilling process.

The invention further provides a downhole telemetry assembly comprising a substantial cylindrical body having at least an annular zone of dielectric material, a toroid and a primary winding therearound located within said dielectric material in said annular zone but of lesser axial length than said annular zone, the primary winding being arranged for connection to an adjacent transmitting or receiving circuit. In one such assembly, the body is of metal and the toroid is positioned in an annular recess in the body, said sleeve co-operating with said recess to define an annular space within which said toroid is located and to define axial spaces between each end of the sleeve and the shoulders of the recess, and a dielectric material filling said annular and axial spaces.

The body may be a drill collar in the form of an integral member, the toroid and sleeve are fabricated within the recess, and the dielectric material is a mouldable material moulded within said space so as to bond the toroid and sleeve in position. Alternatively, the collar comprises two parts removably secured together, the dielectric material is pre-formed in one or more co-operating parts, the toroid and

primary winding being embedded in one of said parts, and said parts inter-fitting to trap the sleeve.

The dielectric material is suitably mouldable, while having suitable mechanical strength, resistance to abrasion, and dielectric properties. One suitable material is Kevlar™.

In another form of the assembly, the collar is entirely moulded of dielectric material with the toroid(s) and primary winding(s) embedded in said collar during the moulding process.

In yet another form of the assembly, the dielectric is formed into a hollow tube that has holes and slots moulded longitudinally around the inside diameter of the tube. Plural toroids are stacked inside the tube with the electrical connections of each toroid fitting into one of the holes and slots. The electrical connections between the toroids are made by inserting a conductive "slug" between the electrical connection of one toroid prior to the installation of the next toroid.

In accordance with a further aspect of the invention, the assembled tube is then centralised in the inside bore of a steel drill collar which has a sub-assembly moulded of the dielectric affixed at its top thus electrically isolating the toroid from the remainder of the steel drill string. In this form the drill collar can also be made of the moulded dielectric.

The invention further provides methods of downhole measurement substantially as described herein.

In all of the described embodiments the toroid assembly is electrically isolated from the main drill string by insulation subs located in the drilling assembly above and below the toroid assemblies. Although not essential in theory, thisarrangement maintains a significant electrical difference of potential between the two sections of the drill string allowing greater current transfer.

BRIEF DESCRIPTION OF THE DRAWINGS

Embodiments of the invention will now be described, by way of example only, with reference to the accompanying drawings, which are briefly described as follows.

Fig. 1a is a longitudinal cross-section of the typical offshore drilling apparatus in the oil industry, including a downhole instrumentation and telemetry system generally embodying the present invention.

Fig. 1b is a longitudinal cross-section of the downhole instrumentation and telemetry system of Fig. 1a in more detail.

Fig. 2 is a plan view of a drilling rig at the surface using the downhole instrumentation of Fig. 1a.

Fig. 3a is a longitudinal cross-section of a toroidal transformer used as a transmitter in the downhole system of Fig. 1a.

Fig. 3b is a longitudinal cross-section of a toroidal transformer used as a receiver in the downhole system of Fig. 1a.

Fig. 3c is a longitudinal cross-section of a toroid assembly utilised as either a transmitter or receiver assembly in the downhole system in Fig. 1a.

Fig. 3d is a perspective view of a toroid assembly utilised as either a transmitter or receiver assembly in the downhole system in Fig. 1a.

Fig. 4a is a longitudinal cross-section of an assembly embodying a toroid transceiver assembly that is moulded around the outer diameter of a steel drill collar.

Fig. 4b is a transverse cross-section through the assembly of Fig. 4.

Fig 4c is a longitudinal cross section of an alternative assembly including separate receiver and transmitter toroid assemblies moulded around the outer diameter of a steel drill collar.

Fig. 5a is a longitudinal cross-section of second embodiment of a transceiver toroid assembly in a drill collar moulded of a dielectric.

Fig. 5b is a longitudinal cross-section of third embodiment of a transmitter toroid assembly and a receiver toroid assembly moulded in separate dielectric drill collars.

Fig. 6a is a perspective view of a fourth embodiment of a toroid assembly.

Fig. 6b is a perspective of the assembly of Fig. 6a.

Fig. 6c is a longitudinal cross-section of a transceiver toroid assembly moulded in a dielectric sleeve for use in the assembly of Fig. 6a.

Fig. 6d is a longitudinal cross-section of embodiment of Figs. 6a-6c.

Fig. 6e is a longitudinal cross-section of separate transmitter and receiver toroid assemblies moulded in respective dielectric sleeves, that can be used in the embodiment of Fig. 6b and 6c in lieu of the transceiver toroid assembly shown in Fig. 6c and 6d.

Fig. 6f is a longitudinal cross-section of the the complete toroid and drill collar assembly in the embodiment of Fig. 6e.

Fig. 6g is a perspective view of a single receiver or transmitter toroid transformer embedded in dielectric material.

Fig. 6h is a longitudinal cross-section of the transformer of Fig. 6g.

Fig. 6i is a perspective view of the assembled embodiment using the single toroid transformers of Fig. 6g to form the receiver and transmitter assemblies for use on the assembly shown in Fig 6a and 6b in lieu of the other embodiments shown in Fig. 6c through 6f.

Fig. 7a is a perspective view prior to assembly of yet another embodiment of a separate receiver toroid assembly for centralised installation inside a drill collar.

Fig. 7b is a perspective view prior to assembly of another embodiment of a separate transmitter toroid assembly for centralised installation inside a drill collar.

Fig. 7c is a longitudinal cross-section of the complete transceiver toroid assembly in the embodiment of Figs. 7b and 7c.

Fig. 7d is a perspective view of a steel drill collar assembly for housing the toroid assemblies of Figs. 7a- 7c.

Fig. 7e is a longitudinal cross-section of the embodiment of Fig. 7a through the complete toroid and collar assembly of Figs. 7a-7d.

Fig. 7f is a longitudinal cross-section of a moulded dielectric drill collar assembly as an alternative for housing the toroid assemblies of Fig. 7a through Fig. 7c.

Fig. 8a is a perspective view of yet another embodiment of a transceiver toroid assembly for installation inside a drill collar assembly.

Fig. 8b is a longitudinal cross-section of the assembly of Fig. 8a.

Fig. 8c is a perspective view of an alternative embodiment havingseparate receiver and transmitter toroid assemblies embodied generally in the same method as that shown in Fig. 8a and 8b.

Fig. 8d is a longitudinal cross-section of a complete collar assembly housing the toroid assemblies of Figs. 8a through 8c.

Fig. 8e is a longitudinal cross-section of another collar assembly housing the toroid assemblies of Figs. 8a through 8c.

Fig. 9a is a perspective view and schematic of a collar and toroid assembly, including electrical switching provided to enable the system to automatically switch from one type of transmitter drive to another to optimise signal reception. This type of switching is incorporated into the preferred telemetry system, no matter what toroid assembly embodiment is used.

Fig. 9b is an equivalent circuit representation of the downhole transmitter as depicted in Fig. 9a when switched to induction mode.

Fig. 9c is an equivalent circuit representation of the downhole transmitter as depicted in Fig. 9a when switched to dipole mode.

Fig. 10a is a block diagram showing the surface system of this invention.

Fig. 10b is a block diagram of the surface receiver and transmitter section of the invention

Fig. 11 is a functional diagram of the surface and downhole transmitter system for this invention.

Fig. 12 is a functional diagram of the surface and downhole receiver system for this invention.

Fig. 13 is a flow chart of the downhole transmitter optimisation process

Fig. 14 is a flow chart of the of the in-operation frequency optimisation process.

DETAILED DESCRIPTION OF THE EMBODIMENTS

Figs. 1a and 2 show respectively a cross-sectional and plan view of a well **1**, drilled by a conventional offshore drilling rig **10** that includes a riser pipe **2**, casing **12**. A drill pipe **20** (also known as drill string) is composed of a number of threaded interconnected tubular pipe sections carrying at their lower end drill collars **21** that include a modified drill collar **23** with insulator sub-assemblies (subs) **22** at the top and bottom terminated by a drill bit **24**. The drill bit is rotated to the right by

conventional means as more drill pipe is added to the drill string **20** to advance the depth of the well **1**.

Mud pumps (not shown) pump drilling fluid **4** down the well **1** through the inside bore of the drill string **20** and out through the drill bit **24**. The fluid **4** returns to the surface via the annulus **3** between the drill string **20** and the well bore **1**. The drilling fluid lubricates and cools the drill bit, transports the strata cuttings to the surface, and prevents the strata **16** fluids and pressure from intruding into the well bore. The composition of the drilling fluid is varied depending on the type of strata and the expected formation pressure to be encountered when penetrating the strata.

Rotary drilling systems typically include a casing pipe **12** extending down the bore hole of the well **1** to isolate the well from aquifers near ground surface or conflicting strata types or conditions. In the case of an offshore well, a riser pipe **2** is run from the rig floor to a template on the seabed and the casing **12** is run through the inside of the riser pipe.

Fig. 1b shows in more detail the information-while-drilling system, which includes a downhole instrumentation and communication system **25** located in the modified drill collar **23** at the bottom of drill string **20** above drill bit **24**.

Fig. 2 shows how a surface data acquisition and communication system **50** is coupled to the top of drill string **40** and riser or casing **41** at the surface. The surface system is also coupled to the downhole system via a horizontal dipole antenna system **42** at the surface. Basically the downhole system **25** measures drilling parameters and strata **16** characteristics, and conveys the data in real time to the surface data acquisition system **50** via drill collars **21**, drill string **20**, casing **12**, riser **2**, water **15**, and various earth strata **16**. The drill collars **21**, drill string **20**, casing **12** and riser **2** provide the necessary conductive path between the systems.

In this embodiment, the communication system uses two toroid assemblies **51** and **52**, one designed for transmission (**52**) and the other designed for reception (**51**). Each toroid assembly consists of a number of individual toroid transformers **34** (for transmission) or **35** (for reception) electrically connected together to form the assembly. The toroid assemblies in the present embodiment are positioned at vertical intervals coaxially encircling the drill collar.

The downhole module assembly **25** is shown packaged and installed in a specially modified drill collar **23** that provides housing for the attachment of the various components of the system. The module assembly **25** is concentrically maintained and electrically isolated from the interior of the drill collar **23** by stabilisers (also referred to as centralisers) **29** moulded in this example of resilient dielectric material.

The down-hole modules are housed within pressure shells moulded of dielectric material (in the same manner as that described below for the embodiment in Fig. 7a), that provides a protective environment for the circuitry contained within. Centralisers **29** position the modules **25** in the internal bore of the drill collar **23**. The housings and centralisers are designed to minimise restriction of the flow of drilling fluid **4** within the drill string **20**.

The module assembly **25** consists of a series of individual modules mechanically and electrically linked together. Some of the modules that make up the assembly are a power module **43**, data communication module **28**, main electronics module **44**, drilling safety module **45**, drilling management module **46**, lithology logging modules **47**, directional module **48**, etc.

The power module **43** consists of a turbine/alternator, power supply, battery charger, and rechargeable battery pack. As the voltage and frequency output of the alternator varies widely, the power supply rectifies, filters, and regulates the output to supply stable power to the down-hole modules and battery charger. The battery is used as a secondary power sources in cases of a turbine/alternator or power supply malfunction during operation. The battery is also used as a power source for the down-hole system if communication is desired for selected data at times when there is no drilling fluid flow.

The data communication module **28** includes a variable frequency and power output phase modulated transmitter for driving the transmitter toroid assembly **52** and a receiver for processing signals from the receiver toroid assembly **51**. Also included is a mode switch for selecting the transmitter drive type, impedance matching circuitry for tuning the transmitter output to the telemetry path impedance, and required power supplies. The data communication module **28** also includes the receiver that filters, amplifies, and demodulates signals derived from the receiver

toroid assembly 35 transmitted by the surface system 50. The communication module 28 sends the demodulated signals to the main electronics module 44 for decoding and execution of the instructions sent from the surface system 50.

The main electronics module 44 includes a computer for controlling the functions of the telemetry system, monitoring and storing operational parameters of the other modules, coding data for transmission, decoding data from the receiver, and executing instructions from the received data. The module controls the frequency and power output through a variable frequency oscillator and a variable output power supply contained with in the transmitter. The module selects telemetry carrier frequencies over a range of 2 Hz to 100 Hz in selectable increments and transmitter output power over a range of 1 watt to 2.5 kW, again in selectable increments. The module also controls the mode switch and impedance matching circuitry of the transmitter and controls pre-programmed timing windows for receiving transmissions from the surface system 50.

The main electronics module 44 also includes a system clock circuit that is synchronised to the surface system clock circuit prior to being run into the bore hole. The system clock places a time stamp with each data measurement recorded in memory in the corresponding sensor module. The time stamp allows stored data to be correlated to surface data, such as depth, when the recorded data is retrieved at the surface. The system clock also controls the transmit and receive time windows which are pre-programmed prior to the system being run into the bore hole. The time windows are specific times at which the down-hole system ceases data transmission to allow the down-hole receiver to receive data from the surface system. To ensure surface data is transmitted at the specified time the down-hole system also transmits a data string to the surface system notifying that it is ready to receive data.

The sensor modules 43, 45 and 46 (but not limited to these), contained in the module assembly 25, process the data from the sensors 60 and transducers 61 and send the processed data to the main electronics module 44 to be coded for transmission to the surface. The main electronics module 44 sends the coded data to the communications module 28 for transmission.

The drilling safety module 45 measures such data as, but not limited to, natural gas content of drilling fluid 4, poison gas content of drilling fluid 4, well annulus 3 and drill string 20 bore pressure, and well annulus 3 and drill string 20 temperature.

The drilling management module 46 measures such data as, but not limited to, bit 24 temperature, drilling fluid 4 annulus 3 and drill string 20 bore flow rate, drill string 20 shock and vibration, weight at the bit 24, torque at the bit 24, and well bore 1 diameter.

The lithology logging module 47 measures such parameters as, but not limited to, formation 16 gamma, resistivity, density, porosity, and pressure.

The directional module measures 48 such parameters as well 1 direction, well inclination, and the high side of the well bore. Some of the parameters are measured by sensors contained within the specific modules pressure housing 90, for example drill string bore pressure, temperature and flow rate, formation gamma, density and porosity, and bore hole directional data. Other parameters measured require the sensors to be contained within the drill collar or special sensor subs, for example bit torque, formation resistivity, and bit weight.

A modified steel collar sub 49 is attached to the bottom end of the collar 23 to receive the power module 43. Several sensors 60 and transducers 61 are attached to the sub 49 at various locations for measuring some of the drilling parameters. The sensors and transducers are electrically connected to the module assembly 25 via wiring harness 26 and fluid-to-air connector 27 in the power module 43.

Further circuit and operational features will described below, with reference to Figs. 9-12.

Referring to Fig. 3a, each individual transmitter toroid transformer 34 consists of a toroid of ferromagnetic core 36 around which is wound a number of turns of an insulated conductor 37. The toroid coil is screened 38 by the use of a copper sleeve and end plates. Ten of these coils 34 are electrically connected in parallel forming a transmitter toroid assembly 52 (see Figs. 3c and 3d).

In a like manner the receiver toroid assembly 51 consists of a number of individual toroidal transformers 35, shown in Fig. 3b. These are constructed in the same manner as the transmitter toroids but are of smaller size as they are not required

to handle such large currents. Ten of these coils **35** are electrically connected in series to form a receiver toroid assembly **51**.

Both the transmit **52** and receive **51** assemblies are located coaxially to the drill collar, either encircling or within the collar, depending on the embodiment. The screening **38** is used to overcome the capacitive coupling effect between the coil and the drill collar. The use of a number of coils connected in parallel to form the transmitter toroid **52** in lieu of a single toroid of sufficient core mass is to overcome the loose coupling effect of the toroid to the collar due to the high impedance of the return current path of the transmission system. This configuration allows a higher output current to be used to drive the assembly while at the same time reducing the inductance seen by the transmitter because of very low mutual coupling. Also, magnetic saturation of the core material sets a fundamental limit on the current that can be induced in the drill string.

The toroidal transformers are virtual electrodes which can inductively couple alternating current **31** flowing in the coil to the drill collar **21** and vice versa. The transmitter toroidal transformer assembly **52** generates an alternating current flow **31**, in the encircled drill collar **21** in response to an alternating current flow in its coil windings. This current flow **30** is also propagated into the surrounding strata. The current flowing in the drill string flows off the drill string and onto the outside of the casing **32** in the cased section of the well bore via low impedance. Due to the characteristics of the cased sections, current will flow virtually unattenuated along the outside of the casing in preference to following an attenuating path along the drill string.

The current flowing in the transmission toroid assembly **52** also produces magnetic waves **30** around the coil that are also propagated into the drill collar, drill string and surrounding strata. Data acquired from the downhole sensor modules can be transmitted to the surface by modulating the alternating currents in the toroidal transformers.

When a toroidal transformer is used as a receiver, an alternating current flow is induced in the coil windings by the flow of the alternating current in the drill collar.

Data pertaining to the lithology of the surrounding strata as well as drilling parameter data acquired by the down-hole module assembly **25** must be

communicated to the surface system **50**. To accomplish this, the transmit toroid assembly **52** is utilised to convey the data to the surface system **50** by inducing phase modulated alternating currents in the drill collar **21** and the drill string **20** for reception by the surface system **50**.

Command and data signals originating in the surface system **50** must also be communicated to the down-hole module assembly **25**. Again, the drill string **20** is utilised as a conductor of the data signal phase modulated alternating current for the purpose of communication. In this case the receiver toroid assembly **51** of the down-hole system receives the transmitted surface signals.

The data can be received at the surface in several different ways. One method is to couple the surface system to the drilling assembly by use of toroid assemblies as described that encircle the drill string **40** and/or casing/riser **41** at the surface. Another method is to use a horizontal dipole antenna **42** to receive the data transmitted by the magnetic waves **30**.

A return path for the modulated alternating currents transmitted in the drill string **20** is provided by the drill string being grounded to the drilling rig through the its contact with the kelly, hook, travelling block, draw works, the rigs earth ground and through the earth's strata and back to the drill bit.

In Figs. 4a and 4b, a combined transmitter and receiver toroid assembly comprises a drill collar **21**, which has an annular undercut in which it receives a dielectric material **39**, and a toroid assembly **34, 35**. The toroid assembly is comprised of a number of individual toroids, which are connected electrically either in parallel or series, dependant on whether it is a transmit assembly **34** or a receive assembly **35**. The assembly is connected via wiring harness **26** and fluid-to-air electrical connector **27** to a data communication module **28** that contains the transmitter and receiver circuitry.

The toroid assemblies **34, 35** are suitably made in sheet form, wrapped in position around the collar **21**, and have their ends butt-joined by welding or soldering to form closed shapes. In this embodiment the dielectric material **39** is applied by vacuum moulding techniques.

The toroid assembly **51, 52** is insulated from the collar by the dielectric **39**. It will be noted that the toroid assemblies **51, 52** and the sleeve are of the same axial extent, and that these are spaced at either end from the shoulders of the collar by a substantial volume of dielectric. These features are of importance for various reasons, such as maintaining a difference of potential between different sections of the drill collar and to prevent short circuiting the transmission system, that is, the remaining drill string. The drill string is in practice grounded at the surface end, as mentioned above.

The assembly shown in Fig. 4c is similar to the one described above, except that the receiver **51** and transmitter **52** toroid assemblies are moulded in separate sections on the drill collar **23**.

The assembly of Fig. 5a is similar to those described above, but with the following modification.

The main drill collar **23** and annular dielectric material **39** of Fig. 4a and 4b are replaced by a unitary dielectric drill collar **70** in which the toroid assembly and screening sleeve are encapsulated. As the dielectric is a material which has suitable mechanical strength, resistance to abrasion and dielectric properties and can be moulded or cast make this embodiment possible. Kevlar ™ is one such material. A modified steel sub **49** is attached to the bottom end of the collar to house the power module **43**.

The embodiment shown in Fig. 5b again is of similar design with the exception that the collar **23** is manufactured of dielectric **39** as two separate sections. The top section contains the receiver toroid assembly **51** and the lower section contains the transmitter toroid assembly**52**. The toroids 35 and copper shields 38 are shown only schematically in Fig. 5b.

Turning to the embodiment of Figs. 6a to 6d, this is of similar geometry to the above embodiment, like reference numerals being used to denote like parts. In this embodiment, however, the collar comprises a steel main mandrel body **70** and a steel end member **71** screw-threadedly engageable therewith to define the annular recess, and the dielectric comprises a main sleeve body **72** engageable butt-wise with end

member **71**. The toroid assembly (**51** and **52**) is moulded into the main body **72**. The dielectric parts in this embodiment do not require being moulded in-situ and can thus, for example, be injection moulded.

This embodiment can readily be assembled and disassembled as indicated in the drawings. This simplifies repair, but at the expense of greater complexity and production cost in comparison with the first embodiment.

The embodiment of Fig. 6e and 6f is similar to those described above, but two separate sleeves replace the single sleeve **72**. The upper sleeve **73** contains the receiver toroid transformers **35** encapsulated in the dielectric **39**. The bottom sleeve **74** contains the transmitter toroid transformers **34** encapsulated in the dielectric **39**.

The embodiment of Fig. 6g through 6i is also similar to those described above except that the sleeves **72**,**73**, and **74** are replaced by ten individual transmitter **54** and ten receiver **53** toroid coils. The toroids are individually encapsulated in a dielectric material, each forming a "doughnut". The doughnuts are installed on the mandrel to form the receiver and transmitter toroid assemblies **51**, **52**.

In Figs. 7a and 7b toroid coil assemblies **51** and **52** are assembled in separate pressure housings **90** moulded of the same dielectric as used in the other embodiments. The pressure housings are moulded with longitudinal holes **94** and slots **95** along its inside bore. The connector tabs **93** of the toroid assemblies are inserted into the slots **95**. The electrical connection between the toroids is achieved by the insertion of a connector "slug" **92** in the connection tab hole **94** as each toroid is installed. This type of packaging eliminates the need for solder connections, thus reducing the possibility of failure under drilling conditions.

This method of construction also allows the toroid assemblies to become an integral part of the centralised module assembly **25**. In this embodiment it is necessary that the centraliser 29 at the top of the assembly is manufactured from a conducting material such as metal or carbon fibre. A conductive path is then provided by metal passing through the centre of the toroid assembly, connected to the drill string by the conductive centraliser. This may be similar to the arrangement shown in US 4,348,672 (Givler).

The embodiment in Fig. 7c is similar to the embodiment described in Fig. 7a and 7b with the exception that both the receiver 51 and transmitter 52 toroid assemblies are housed in a single moulded pressure housing 55 to become an integral part of the centralised module assembly 25.

The drill collar assembly in Figs. 7d to 7f for housing the above described embodiments comprises a top annular sub 22 screw-threadedly engageable to the top of a standard drill collar 81 with a bottom annular sub 22 screw-threadedly engaged. Figure 7d is a perspective view of the drill collar assemble for housing the centralised embodiments described above. Figure 7e shows a cross-sectional view of Fig 7d which is made up of top and bottom insulation subs 22 and a standard steel drill collar 81 having the receiver 51 and transmitter 52 toroid modules installed along with the main electronics module 44 and the data communications module 28. The top and bottom subs 22 are identical in construction and are moulded of dielectric, which has suitable mechanical strength, resistance to abrasion and dielectric properties, which electrically isolate the drill collar between the two subs from the rest of the drill string. In this embodiment the module assembly 25 is concentrically housed in the bore of the drill collar. The modules are concentrically maintained and electrically isolated from the interior of the drill collar by stabilisers 29 moulded of resilient dielectric material.

The drill collar assembly of Fig. 7f is similar to the assembly described above, except the drill collar 82 is moulded of dielectric and the top and bottom subs 19 are made of steel. The toroid modules 51 and 52 are the same as described above.

In both of the above described drill collar assemblies the single transceiver module 55 of Fig 7c replaces the individual receiver and transmitter toroid modules 51 and 52 in module assembly 25.

In Figs. 8a and 8b a transceiver toroid assembly is formed from receiver and transmitter toroid transformers. The transceiver toroid assembly is assembled in a pressure housing 56 of similar construction to that described in the embodiment of Figs. 7a and 7b with the exception that the housing is larger in diameter and has a central hollow longitudinal shaft 57 moulded down the centre of the housing. The longitudinal hollow shaft 57 extends out-with both ends of the pressure housing and

contains grooves **64** for o-ring **62** and back-up ring **63** seals to isolate the housing from fluid intrusion. In substance the pressure housing becomes an integral part of the drill collar and drilling fluid flows uninterrupted through the hollow central shaft **57**.

The embodiment in Fig. 8c is similar to that described for Figs. 8b and 8c with the exception that the receiver and transmitter toroid transformers are assembled in separate housings forming individual receiver **58** and transmitter **59** modules.

The drill collar and toroid assemblies in Fig. 8d and 8e each comprise a top annular sub screw-threadedly engageable to the top of a drill collar and a similar bottom annular sub screw-threadedly engageable to the bottom end of the drill collar. Fig. 8d is a cross-sectional view of an assembly which is made up of insulation subs **22** and a steel drill collar **65** having the receiver **58** and transmitter **59** toroid modules installed along with the main electronics module **44** and the data communications module **28**. The top and bottom subs are identical in construction and are moulded of dielectric, which has suitable mechanical strength, resistance to abrasion and dielectric properties, which electrically isolate the drill collar between the two subs from the rest of the drill string. In this embodiment the module assembly **25** is concentrically housed in the bore of the drill collar. The modules are concentrically maintained and electrically isolated from the interior of the drill collar by stabilisers **29** moulded of resilient dielectric material.

The drill collar and toroid assembly of Fig. 8e is similar to the assembly described above, except the drill collar **66** is moulded of dielectric and the top and bottom subs **19** are made of steel. The toroid modules **58** and **59** are the same as described above.

In both of the above described drill collar assemblies the single transceiver module **56** of Fig. 8d replaces the individual receiver and transmitter toroid modules **58** and **59**.

In operation, data acquired by the down hole module assembly **25** must be communicated to the surface system **50**. This is accomplished by the transmit toroid assembly **52** inducing phase modulated alternating current in the drill collar **23**, riser/casing **12**, and the drill string **20** for transmission to the surface system **50**. The transmit toroid assembly **52** also induces em waves into the surrounding strata, water

(if on offshore location) and into the atmosphere which in these embodiments are also received by the surface system.

Data and operational commands must also be communicated to the downhole assembly via the surface system **50**. This is accomplished, again, by use of the drill string **20**; casing/riser **12** and drill collar **23** as the conductor of phase modulated alternating current for the purpose of communication. The down hole system uses the receiver toroid assembly **52** to detect the transmitted data signals.

The surface system **50** is coupled to the drill string and riser/ casing via similar transceiver toroid assemblies as those in the downhole system. The drill string transceiver toroid assembly **40** is mounted below the rig rotary table allowing the drill string to be removed from or run into the wellbore without the need of removing the toroid assembly. The riser/casing transceiver toroid assembly **41** is also installed below the rig floor around the casing/riser and below any slip joint if one is used in the riser system.

Optimisation of the communication system is accomplished in this invention by its ability to continuously monitor the ever changing inhomogeneous environment in which it operates and vary its operating parameters. The system can change its mode of transmitter drive from an induction communication system to a Hertzian dipole antenna system.

Referring to Figs. 9a and 9b, the downhole system contains an electronic switch **110**. In induction mode, switch **110** electrically connects the modified steel drill collar **23** to the drill string above the isolation sub **22** and electrically connects both sides of the transmitter toroid assembly **52** to the transmitter outputs. In this mode the phase-modulated alternating current flowing through the transmitter toroid assembly **52** induces a current flow in to the drill string **20** which flows to the surface. The alternating current flowing in the transmitter toroid assembly also produces alternating magnetic wave fronts that are transmitted through the surrounding medium to the surface. If the system determines from the data it has acquired while monitoring its electrical environment that an alternative drive mode would be more effective it can activate the electronic switch **110** and change from an induction drive system to a dipole drive system.

If the electronic switch **110** is activated and changes from the induction mode to the dipole mode (Fig. 9c) the switch electrically connects the negative leg of the transmit toroid assembly **52** to the drill string **20** above the insulator sub and grounds the negative leg of the transmitter by connecting it to the drill string below the modified collar 23. In this mode the transmitter toroid assembly **52** becomes a load coil for the drill string **20** which acts as a dipole antenna. In this mode the phase modulated alternating current is also induced into the drill string along with em wave fronts to transmit the data to the surface. The skilled reader will appreciate that "negative" and "positive" are used in this context merely to establish a convention: the signals are a.c. only, and the polarity of components can also be reversed.

Fig. 10a shows how the surface system **50** includes a master controller assembly **100**, A data acquisition assembly **101**, a drill string transceiver assembly **40**, a riser/casing transceiver assembly **41**, and an EM wave receiver antenna assembly **104**. The system also includes surface data sensors **105**, a satellite positioning system **106**, and several input **108** and output **109** devices.

The master controller assembly **100** controls the overall operation of the surface and downhole systems. A high speed computer provides the operational control, and all its operating peripherals (not shown) contained within the assembly and interfaced with the other assemblies in well known methods in the industry. The master controller also contains a system clock circuit which functions in the same manner as the down-hole system clock as previously described.

The assembly **100** generates all command signals and pre-programmed instructions for the operation of the down-hole system. The command signals can be manually entered via the input devices **108**, such as a keyboard, voice recognition circuitry or touch sensitive visual display units. The master controller assembly **100** also interfaces to various surface data acquisitions systems **107** for integration of all drilling data, both surface and down-hole for display, storage, and communication to remote locations via the output devices **109**, such as tape or disk drives, printers, plotters, visual display units or modems.

The master controller assembly **100** controls the operation of the telemetry system, contained in the data acquisition assembly **101**, in a similar manner to the

main electronics module in the downhole system. The difference is that the surface telemetry system uses only an induction drive for the transmit toroid assemblies **40** and **41**. This is because the isolation necessary for the Hertzian dipole arrangement is not readily compatible with the drilling operation. On the other hand, the power available for transmission from the surface to the downhole system is not so limited, so that inefficiencies in the induction method in particular conditions can be overcome simply by an increase of power.

The master controller assembly **100** also includes a system clock circuit that is synchronised to the down-hole system clock circuit prior to being run into the bore hole. The system clock places a time stamp with each surface sensor data measurement recorded in memory. The time stamp allows correlation of surface and down-hole data, such as depth to formation resistivity, when recorded data is retrieved from the downhole system once it returns to the surface. The system clock also controls the transmit and receive time windows which are pre-programmed prior to the system being run into the bore hole. The time windows are specific times at which the down-hole system ceases data transmission to allow the down-hole receiver to receive data from the surface system. To ensure surface data is transmitted at the specified time the down-hole system also transmits a data string to the surface system notifying that it is ready to receive data.

The data acquisition assembly **101** includes the surface transmitter and receiver circuitry as well as the required circuitry for interfacing with surface drilling parameter data sensors **105**. The assembly **101** also includes the interface circuitry for a satellite positioning system **106** used for pre-programming alignment of the directional module of the downhole assembly to the well surface location prior to running into the bore hole.

The data acquisition assembly also includes a data string verification circuit that verifies each data string received contains all data bits required to form a complete string and that all measurements contained in the string met specific tolerances for each particular measurement. The data string received by each of the three surface receiver assemblies are input into the circuit for verification. If all three data strings are verified the system selects one for processing. If none of the strings

pass verification the circuit then merges the three strings to see if a complete data string can be formed which will pass verification.

The functions of data acquisition assembly **101** include transmitting instructions and data to the down-hole system, detection of data from the down-hole assembly, and processing and converting the data received from the down-hole system into a format suitable for output to the master controller assembly **100**. Also the assembly measures such surface parameters as mud pump strokes, standpipe pressure, weight on bit, rotary table rpm, rotary torque, bit depth, and well depth. The master controller assembly **100** controls the data acquisition assembly **101** functions.

The drill string transceiver assembly **40** consists of a transmitter and receiver toroid assembly similar to the down-hole assembly described in Fig. 6e-6f but is constructed of such physical size as to allow the drill string to pass unobstructed through the centre of the assembly. The assembly functions as described for the downhole system. The assembly is installed below the drill floor and under the rotary table in such a manner as not to obstruct normal drilling operations.

The casing/riser transceiver assembly **41** is similar to the drill string transceiver assembly **40** but is constructed of such physical size and in such a manner as to allow it to be installed around the casing or riser. The assembly functions as described for the downhole system. When the assembly **41** is installed around the casing it maybe located either above or below the blow-out preventers. When the assembly is being installed around the riser it is preferably installed below the slip joint. If the assembly needs to be installed above the slip joint, electrical continuity should be obtained somehow between the top and bottom portions of the slip joint. It will be appreciated that the casing provides a relatively smooth conduction path for signals, once they are coupled into the casing, compared with the drill pipe, which has many impedance discontinuities caused by the heavy joints. Accordingly, detecting signals from the top of the casing provides much of the benefit of the transceiver coils which MacLeod places at the bottom of the drill string, without the expense and difficulties involved.

Both toroid assemblies 40 and 41 can be constructed in two halves, hinged or otherwise connected, for ease of installation around the drill string and casing.

The EM wave receiver antenna assembly **104** consists of two radially extended insulated electrical conductors as shown in Fig. 2. The conductors may for example be laid directly upon the ground (for on-land locations), or be strapped to the hand rails around the perimeter of an off shore drilling rig or platform. Although the radial receiving arms are located around the drilling rig or platform, they are not in electrical contact with the drilling rig or platform.

The subject intelligent EM telemetry system,formed by the surface **50** and down-hole assemblies **112**, provides the communication link for transmission of command and data signals between the surface and downhole environments. Communication is accomplished using an optimised carrier frequency signal quadra-phase modulated with data signals containing command and/or data. Other coding schemes are possible, and the type of coding may be adaptive so as to optimise data rate under varying conditions. The carrier signals are conducted between the surface data acquisition assembly **101** and down-hole data communication module **28** to different extents via the conductive drill string and the surrounding media. The frequency of the carrier signal is selected via the system from a range of frequencies between 2 Hz and 100 Hz to offset attenuation that normally increases as the well depth increases. Also, the system selects the optimum drive mode of the transmitter, matches the transmitter drive impedance to the conductive media impedance, and optimises the transmitter power output in order to reduce the effects of attenuation and noise on the transmitted signals.

The data signals encoded onto the carrier frequency by the down-hole assembly are received, Fig. 10b, by the surface data acquisition assembly **28** through the receiver toroid assemblies **40** and **41** and also via the em wave receiver antenna. The signals are input into the receiver circuitry **113** and **114** through a shunt circuit **111** and a digital frequency spectrum analyser circuit **116** to the receivers **113** and **114**. The shunt circuit **111** attenuates the received signal, to avoid overdriving the receivers during the surface system's measurement of the telemetry path's impedance level. The master controller assembly **100** controls the use of the shunt circuit **111**. The master controller **100** bypasses the shunt circuitry **111** when the surface system is receiving data from the down-hole system. The digital frequency spectrum analyser circuit **116** monitors background electrical noise of the telemetry path during non-

transmission periods to optimise the receiver filters band width. The master controller assembly also controls this process. The signals are amplified, filtered, demodulated, verified, decoded, and converted from analogue to digital output, by the receiver circuitry **113** and **114** in the data acquisition assembly **101**, for use by the master controller assembly **100**. The data string verification circuitry **115** functions as described above.

Fig. 11 shows the receiver assembly in more detail. This contains a shunt circuit **111**, a dual digital passive bandpass filter **130**, a pre-amplifier **131**, an automatic gain controlled amplifier **132**, a digital variable bandpass filter **133**, a second stage automatic gain controlled amplifier **134**, a second stage digital variable bandpass filter **135**, a phase locked loop **136** for demodulation, a third stage automatic gain controlled amplifier **137**, a data string verification circuit **115**, and an analogue to digital converter **139**. Functionally, the carrier current generated and modulated by the downhole assembly telemetry system is sensed at the surface by the receiver toroid assembly in the two transceiver toroid assemblies **40** and **41** and the EM antenna **104** and directed to the dual digital passive bandpass filter **130** via the shunt circuit **111** and the digital frequency spectrum analyser **116**. The shunt circuit and digital spectrum analyser functions as described above. The passive filter **130** removes the frequencies of background noise in a frequency range determined by the master controller assembly **100**. The signal is then passed to the pre-amplifier 131 for amplification. Next, the detected signals are passed through an automatic gain controlled amplifier **132**, a digital variable bandpass filter **133** for a frequency range determined by the master controller assembly **100**, a second stage automatic gain controlled amplifier **134**, and a second stage digital variable bandpass filter **135** that also has its frequency range determined by the master controller assembly **100**. Finally, the signals are passed through a phase lock loop **136** for demodulation, a third stage automatic gain controlled amplifier **137**, the data string verification circuitry **115**, and an analogue to digital converter **139** for input to the master controller assembly **100** for processing, storing, and displaying.

Command and/or data signals obtained by the master controller assembly **100** via the input devices or surface sensors for communication to the down-hole system

are processed and coded for transmission by the master controller assembly **100**. The master controller assembly **100** sends the coded data and instructions to the transmitter circuitry, Fig. 12, in the data acquisition assembly. The code data is input into quadra-phase shift modulator **124** that modulates a variable frequency oscillator **123** that produces the carrier frequency determined by the surface and down-hole telemetry systems. Next, the coded carrier frequency is input into a variable power output power amplifier **121** that boosts the power to the level determined by the master controller assembly **100**, then passes through the variable impedance matching device **120** and drive mode switch **110** to the transmitter toroid assemblies within the drill string **40** and casing/riser **41** transceiver assemblies. An output power sensor **125** monitors the power level of the transmitter output across the impedance matching device **120**, which in turn, is controlled by a variable power output controller **122** via the master controller assembly.

Impedance matching device **120** may comprise for example a variable tap transformer. Alternatively, a further set of toroidal coils could be provided, switchable between different series & parallel configurations, to match the impedance of the medium to that of the drive circuit. The down-hole communication system is functionally similar to the surface communication system including the receiver for receiving the modulated carrier signal, containing surface data and command instructions, generated by the surface communication system transmitter. The downhole system also includes a transmitter for generating modulated carrier signals containing downhole data measurements for transmission to surface system. The downhole system uses only one of the transceiver embodiments described in this text for communication with the surface.

Operation of the system described above will now be described in detail.

The central electronics module in this embodiment selects the type of transmitter drive system to be used and electronically switches the transmitter toroid assembly from an induction drive method to a vertical dipole method.

When the system is in the induction drive mode, both leads of the transmit toroid assembly are electrically connected to the transmitter output and an alternating current is caused to flow through the toroid windings which develops a magnetic field inducing an oscillating current in the drill collar. If a high resistivity formation is

encountered below the transmitting toroid assembly, the strata below may not act as a ground plane, or return current path. The drill string may then be treated as a vertical dipole. That is, the module connects, the "negative" lead of the transmit toroid to the drill string above the top insulator sub and connects the "negative" output of the transmitter to the drill string below the bottom insulator sub, that is of a different electrical potential difference, thus forming a dipole antenna circuit. The drill string then acts as a dipole antenna and the transmit toroid assembly acts as the load coil for the antenna. Thus the alternating current output of the transmitter flows through the transmit toroid assembly directly into the drill string above the top insulator sub and to the surface for reception. As the alternating current flows through the transmit toroid assembly it produces alternating magnetic waves which are induced into the surrounding medium and propagated to the surface for reception by the surface horizontal dipole antenna system.

In both drive methods the telemetry signal path flows though the drill string above the top insulator sub to the surface, through the rig earth ground, and lastly through the earth strata to the bottom section of the drill string below the bottom insulator sub, thus forming the completed circuit.

The drill string (signal path) can be modelled as a transmission line, or rather a series of transmission lines, with a characteristic impedance that varies from medium to medium. One of the major influences on the impedance in the telemetry signal path is the length of drill string below the transmit toroid assembly. As the down-hole measuring system is by its nature located as near to the bit as possible, this length can be quite short. Research carried out has shown that even for a telemetry signal path of otherwise low characteristic impedance, a short length of drill string below the toroid can result in high drive impedance. It can be shown that this drive impedance is primarily resistive, so that the impedance of the length of drill string below the transmit toroid assembly can be determined mathematically.

The central electronics module in the embodiments matches the impedance of the transmitter output to the impedance of the telemetry signal path for the selected drive mode. If the module selects the induction type drive as the optimum mode the module then matches the impedance of the section of drill string below the top isolation sub to the transmitter output. This is required for the module to select the

optimum power output of the transmitter, and to ensure that the transmitter is impedance matched to the telemetry signal path impedance. The central electronics module is pre-programmed with well known electrical formulae for calculating impedance, and the length of the drill string below the transmit toroid is input into the prior to it being run into the well bore for use in the impedance determination.

The module also matches the transmitter output to the remainder of the telemetry signal path by use of the measured telemetry signal path impedance as described above. Further research has shown that the telemetry signal path impedance can vary from fractions of an ohm to several thousand ohms. Thus the communication module uses a variable impedance matching device, either tapped transformers or series/parallel connection of a number of coils (for example toroids), to match the impedance of the transmitter and transmit toroid assembly to the signal path. If the dipole drive mode is selected, the impedance matching procedure is the same as described above except that the matching of the section of drill string below the bottom insulator sub is not required.

The attenuation factors that can be tolerated by the telemetry signals are dependent on the power available in the transmitter. The transmitter power required depends upon the drive impedance and the signal amplitude required by the receiver at a given carrier frequency. As successful data telemetry is dependent on the transmitter's ability to deliver power to a wide range of impedances, from fractions of an ohm to several thousand ohms, the transmitter power in these embodiments can be varied through a range of 1 watt to 2.5 kW. The central electronics module selects the transmitter output power over this range.

The adaptive setting of transmission parameters will now be described. As the telemetry signal path electrical environment is inhomogeneous and continuously changing the carrier frequency must be able to function over a large range of attenuation factors. In such an environment it has been found that only very low frequencies can successfully operate under such conditions. Telemetry communication is accomplished in the present embodiments by using a transmitter and receiver that are operable over a range of frequencies between 2 Hz and 100 Hz to offset the range of attenuation experienced. The attenuation normally increases as the

well deepens; thus the carrier frequency is normally decreased to offset the increased attenuation.

Refering to Fig. 13, the downhole electronics module selects the optimum carrier frequency by first measuring (S1302) the signal path attenuation, as described previously in relation to the tenth aspect of the invention. Using this result and a set of rules that may be embodied in a look-up table, the module selects (S1304) an initial frequency from a set of predetermined frequencies. The downhole transmitter then transmits (S1306) then begins transmitting at the selected frequency, with, say, half maximum power. During this time, the surface receiver is scanning and listening for the transmitted signal at all frequencies, and the downhole receiver is listening for a response, at the same frequency as is selected for transmission (later, the up- and down-hole transmission frequencies may be optimised to different values). As soon as the surface receiver locks on to the signal from downhole, it signals (S1308) the quality of the signal to the downhole system, and an optimisation process begins.

If no response is received from the surface within a preset time, the downhole module implements a sequence of adjustment to improve signal strength at the surface step by step until a response is received. The first stage of this process is to increase power in relatively large steps, while staying at the selected frequency. If no response is received despite the increased power, then a second stage adjustment is made, reducing the frequency in a large step, and then increasing power again if no response is received. These measures are repeated until the surface system eventually locks on to the signal and its reply is received by the downhole system.

Once two-way communication is achieved between the surface and downhole systems, a frequency optimisation process is implemented (S1308-S1314). This involves the downhole module sweeping a selected range of frequencies either side of the selected frequency, through a predetermined frequency interval, and determines the frequency at which the surface receiver measures the maximum signal amplitude for a given set transmitter voltage output. The module then (S1316) sets the transmitter frequency to the optimum frequency to be used as the carrier frequency, as instructed by the surface system.

Next, a power optimisation process is implemented (S1318-S1326). The downhole module then commands the transmitter to sweep the range of power outputs

while the surface system monitors the signal amplitude and signal-to-noise ratio to determine the optimum power output for signal transmission. At the conlcusion of this process, surface system sends (S1328) a command signal to the downhole system when an acceptable signal amplitude and/or signal-to-noise ratio is achieved. The central electronics module then commands the transmitter to use that particular power output for transmission. An optimum power setting below the maximum available is preferable to avoid possible component failure due to factors, such as heat damage, caused by long term operation at high powers. In the event that a useable signal strength cannot be attained within a frequency interval the module then selects another frequency interval and re-commences the optimisation process.

In the event that optimisation is not obtained within the selected frequency interval, control passes from step S1312 or S1324 to step S1330, where a new frequency interval is selected, and the optimisation processes repeated.

The central electronics module continually optimises the telemetry parameters during operation. A flowchart for the optimisation process is shown in Fig. 14. For example, when the central electronics module determines that the carrier frequency requires changing to experience less attenuation and/or provide a better signal-to-noise ratio the module transmits (S1402) notification to the surface system that it is going to sweep the carrier frequency range. It commands the downhole transmitter to sweep the carrier frequency range and the surface system monitors the signal levels detected for determining the carrier frequency having the greatest signal amplitude and/or the best signal-to-noise ratio (S1406-S1412). The surface system then (S1414) commands the down-hole system to utilise that particular frequency for the carrier signal.

The respective surface receiver and down-hole transmitter can also select the optimum telemetry carrier frequency, also illustrated by flowchart in Fig. 14. For example, in a "surface interrupt routine", the surface receiver detects (S1416) low signal amplitude and/or signal-to-noise ratio. It then (S1418) sends a command to the down-hole system to sweep a range of frequencies while it monitors the received signal parameters to identify the frequency which produces the desired signal parameters for optimum operation. The processing is then the same (S1404 etc) as if the downhole system had initiated the frequency sweep. The surface system notifies

the down-hole system of that frequency and the central electronics module sets the transmitter carrier frequency to that optimum frequency. This method can be used by the system for optimising each variable parameter of the telemetry system.

Similar optimisation procedures can be implemented for the surface-to-downhole communication, Of course, other protocols for opitimising commuication parameters are readily conceivable.

If the telemetry system is switched to the dipole drive mode, the central electronics module can also determine the optimum carrier frequency for this drive mode by sweeping a range of frequencies at a set transmitter power output and determining at what frequency the maximum receiver voltage is detected. The most efficient carrier frequency for the dipole drive mode is the resonant frequency or tuned frequency for the drill string under the particular conditions existing at that time. The central electronics module downhole also stores the attenuation, signal amplitude, signal-to-noise ratio, drive impedance, power output, and optimum frequency data in memory to form a telemetry database. The system would then use this database to select a carrier frequency as a starting point, for known telemetry signal path parameters, and sweep by a set frequency range either side of the selected frequency to fine tune the optimum carrier frequency. An additional benefit of this system is that from the operating data thus accumulated a knowledge base of operating conditions may be built allowing the quick and safe operation of equipment in a variety of conditions.

Switching between dipole and induction modes could in theory be effected as another variable in such optimisation processes as are described above for frequency and power optimisation. In the present embodiment, however, the transmission mode is decided separately, in response to measured parameters of the environment. In particular, if a high-resistivity formation is encountered by the drill bit, it can be predicted that the dipole mode will soon become unfavourable. This is because the dipole antenna relies on the conductive "ground plane" provided by the surrounding strata. In such circumstances, the system can be switched, by manual command or automatically, to the induction mode.

Normal transmitting operation may be interrupted at any time to allow for the transmission of urgent messages. This may occur, for example, when a safety module

detects hazardous gases or dangerous operating environments. A high priority can be assigned to such messages in the communication protocols. Moreover, in addition to sending the initial alarm, the downhole system may alter the priorities of other message types to provide better monitoring of the safety situation, for so long as the hazard continues, or until the alarm condition is cancelled from the surface. Such a feature can be implemented in telemetry systems, independently of the other features of the present embodiments, described above.

1. A downhole apparatus for providing data communication by electromagnetic (EM) radiation between a downhole location and a surface station, the downhole apparatus including means for transmitting data from beneath the surface of the earth to a receiving station, and means for receiving data transmitted by the surface station, wherein separate transmit and receive coils are provided for said transmitting and receiving means respectively.

2. A downhole apparatus as claimed in claim 1 wherein the transmit coil comprises a plurality of coils connected in parallel.

3. A downhole apparatus as claimed in claim 1 or 2 wherein said receive coil comprises a plurality of coils connected in series.

4. A downhole apparatus as claimed in claim 1 wherein the transmit coil comprises a plurality of individual coils connected in parallel, the receive coil comprises a plurality of individual coils connected in series, all the individual coils being of identical construction.

5. A downhole apparatus as claimed in any preceding claim wherein the transmit coil is arranged to be aligned with the axis of an electrically conductive drill string.

6. A downhole apparatus as claimed in claim 5 wherein said transmit coil is arranged to be electrically connected to said drill string.

7. A downhole apparatus as claimed in claim 5 wherein said transmit coil is arranged to be electrically isolated from said drill string.

8. A downhole apparatus as claimed in claim 7 adapted for inclusion in a drill string, said electrical isolation being provided by a dielectric material arranged to form the entire mechanical connection between the apparatus and other elements of the drill string.

9. A downhole apparatus as claimed in claim 5 further comprising selection means for selecting a first mode wherein said transmit coil is electrically connected to said drill string and a second mode wherein said transmit coil is electrically isolated from said drill string.

10. A downhole apparatus as claimed in claim 9 further comprising control means for operating said selection means to switch modes during downhole operation.

11. A downhole apparatus as claimed in claim 10 wherein said control means includes means for operating said selection means automatically in response to environment-dependent conditions detected during communication.

12. A downhole apparatus as claimed in any preceding claim wherein said transmit coil is a toroidal coil.

13. A downhole apparatus as claimed in any preceding claim wherein said receive coil is a toroidal coil.

14. A downhole apparatus as claimed in any preceding claim 12 or 13, wherein a cylindrical conductive shield is provided within the bore of said coil.

15. A downhole apparatus as claimed in any preceding claim further comprising means for detecting environment-dependent conditions and means for adjusting at least one parameter of the transmitting means in response to said conditions.

16. A downhole apparatus as claimed claim 15, wherein said detecting means includes means for analysing signals emitted by said transmit coil and detected by said receive coil.

17. A downhole apparatus as claimed in claim 15 or 16, wherein said parameter adjusting means is responsive to command signals received from the surface station by said receiving means.

18. A downhole apparatus as claimed in claim 17 wherein said parameter adjusting means includes means for autonomously implementing a parameter adjusting sequence to establish communication with the surface station in the absence of said command signals.

19. A downhole apparatus as claimed in any of claims 15 to 18, wherein said parameter is one of:

- transmit power ;

- drive impedance;
- carrier frequency;
- modulation type;
- data coding; and
- dipole versus inductive drive mode.

20. A communication system including a downhole apparatus as claimed in claim 15 or 16 in combination with a surface station, wherein said detecting means includes means at the surface station for analysing signals emitted by said transmit coil and received at or near the surface, and said parameter adjusting means is responsive to further signals received from the surface station by said receiving means.

21. A system as claimed in claim 20, wherein said analysing means at the surface is arranged to receive and compare signals received by plural reception antennas in order to control the adjustment of said parameter(s).

22. A system as claimed in claim 21, further including said plural antennas, the antennas comprising two or more of:

- a coil surrounding a drill string on the deck of a drilling rig;
- a coil surrounding a riser casing below the deck of a drilling rig; and
- a horizontal dipole antenna comprising a conductor extended generally parallel to the surface.

23. A downhole apparatus for providing data communication by electromagnetic (EM) radiation between a downhole location and a surface station, the downhole apparatus including means for transmitting data from beneath the surface of the earth to a receiving station, wherein transmit coils are provided for said transmitting means, the transmit coil comprising a plurality of coils connected in parallel.

24. An apparatus for use in transmitting data by electromagnetic (EM) means between a downhole location and a surface station comprising a transmit coil arranged to be aligned with the axis of an electrically conductive drill pipe, the apparatus further comprising selection means for selecting between a first mode wherein said transmit coil is electrically

connected to said drill string and a second mode wherein said transmit coil is electrically isolated from said drill string.

25. A downhole apparatus for providing data communication by electromagnetic (EM) radiation between a downhole location and a surface station, wherein a transmit coil is provided for transmitting data to the surface station, the apparatus comprising means for detecting environment-dependent conditions and means for adjusting at least one parameter of said transmitting means in response to said conditions, said detecting means comprising a receive coil within the downhole apparatus, close to but separate from the transmit coil, and means for analysing signals emitted by said transmit coil and detected by said receive coil.

26. A downhole communication system comprising a downhole apparatus and a surface station, for providing data communication by electromagnetic (EM) radiation between a downhole location and the surface, the downhole apparatus comprising data transmitting and receiving means, the system including means for detecting environment-dependent conditions and means for adjusting at least one parameter of said transmitting means in response to said conditions, wherein said detecting means are provided at the surface station for analysing signals emitted by said transmit coil and received at or near the surface, and said parameter adjusting means is arranged to respond to further signals received from the surface station by said receiving means.

27. A system as claimed in claim 26 wherein said detecting means is arranged to receive and compare signals received by plural reception antennas in order to control the adjustment of said parameter(s).

28. An apparatus for receiving data signals transmitted from a downhole location by electromagnetic (EM) radiation, the receiving apparatus including a coil surrounding a riser casing below the deck of a drilling rig for the reception of said EM radiation.

29. An apparatus for receiving data signals transmitted from a downhole location by electromagnetic (EM) radiation, the receiving apparatus including a horizontal dipole antenna comprising a conductor extended generally parallel to the surface.

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Application No: GB 9928480.4 **Examiner:** Glyn Hughes
Claims searched: 1 to 8, 12 to 19 **Date of search:** 2 June 2000

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Search Report under Section 17

Databases searched:

UK Patent Office collections, including GB, EP, WO & US patent specifications, in:

UK Cl (Ed.R): E1F (FHK), H4L (LCAX, LCC, LCX)

Int Cl (Ed.7): E21B 47/12, G01V 3/24, 3/26, 3/28, 3/30, 3/34

Other: Online: WPI, EPODOC

Documents considered to be relevant:

Category	Identity of document and relevant passage		Relevant to claims
X, Y	GB 2292869 A	(INTEGRATED DRILLING) see Fig.1, page 5 lines 14-20, page 7 lines 2-11, page 9 lines 1-4	X: 1,5,7 Y: 12, 13 at least
X, Y	GB 2153410 A	(LICENTIA) see whole document	X: 1,5,7 Y: 12, 13 at least
X	EP 0295178 A2	(SCHLUMBERGER) see fig.6, page 6 lines 7-15	1,5,7,12, 13 at least
X, Y	US 4800385	(RADIC) see figure 3	X: 1,5,7 Y: 12, 13 at least
Y	US 4739325	(MACLEOD) see figs. 3, 4	12, 13 at least

X	Document indicating lack of novelty or inventive step	A	Document indicating technological background and/or state of the art.
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